# $M_W$, $Z$ $A_{fb}$, and $W/Z$ Production

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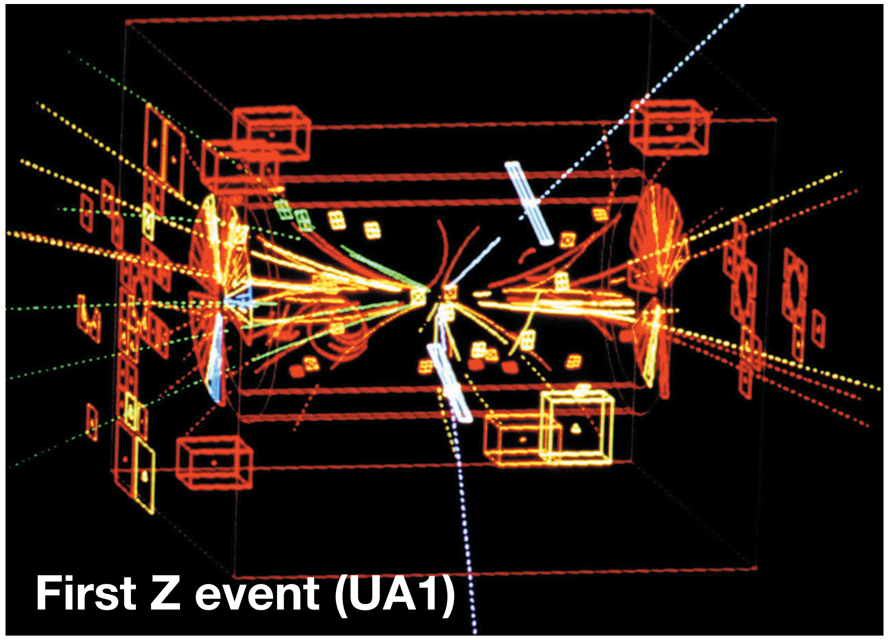
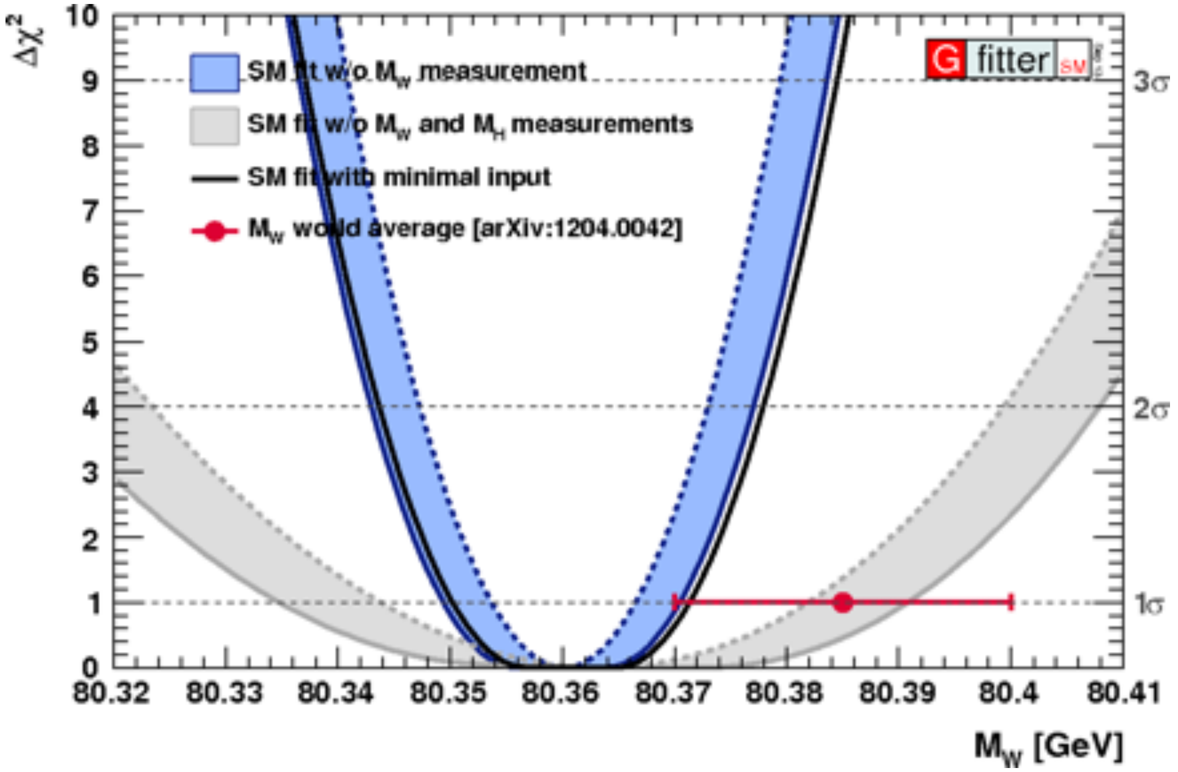
# W/Z physics at hadron colliders

- Long history dating back to the discovery of the W and Z (1983)
- From discovery to standard candle: Tevatron, LHC
  - Crucial for understanding detectors at each new energy
- Important for constraining PDFs
- Background to many new physics searches
- Essential quantities in the SM
  - **Precision measurements**
  - Can shed light on potential new physics



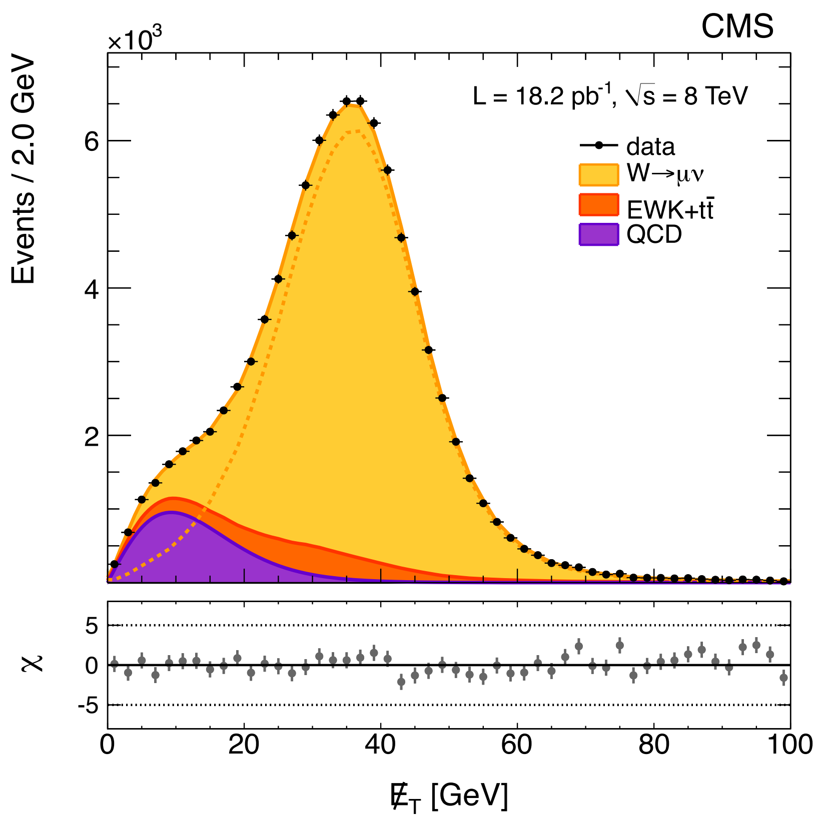

**1.** W/Z production measurements

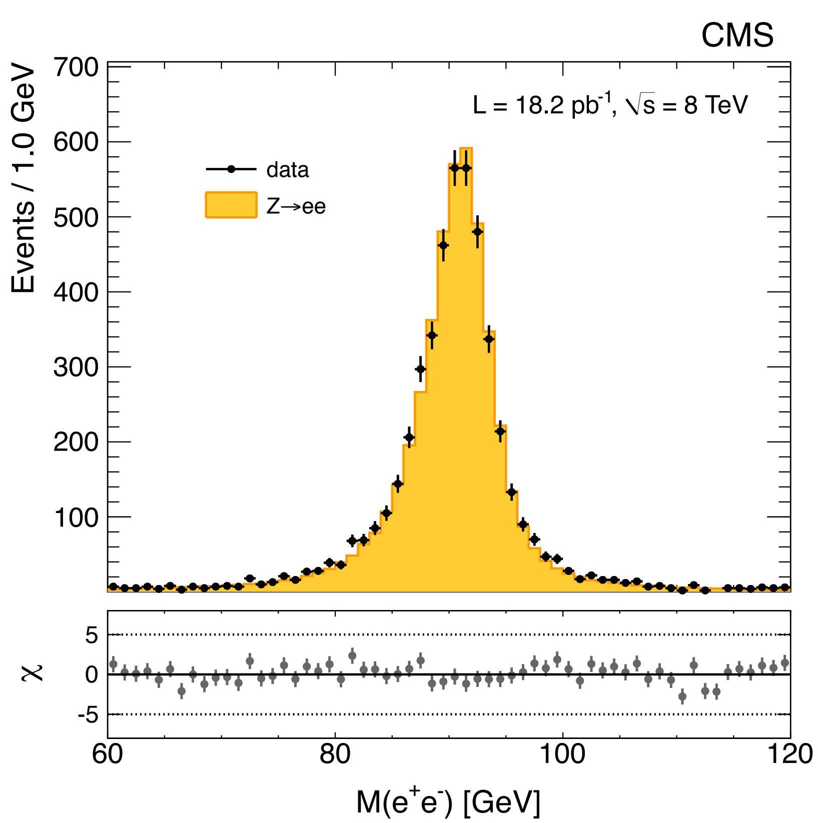
**2.** W boson mass

**3.** Asymmetry measurements

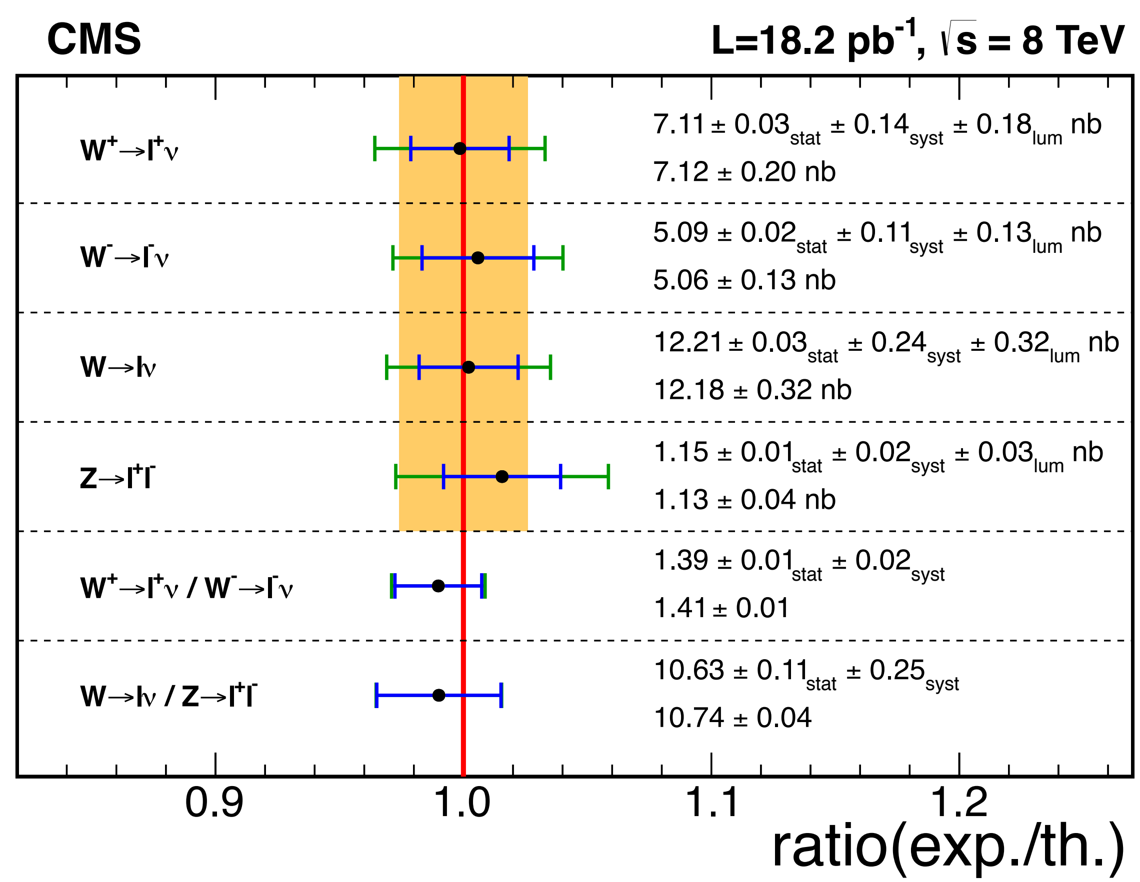
# W and Z production

# Inclusive W and Z production at 8 TeV



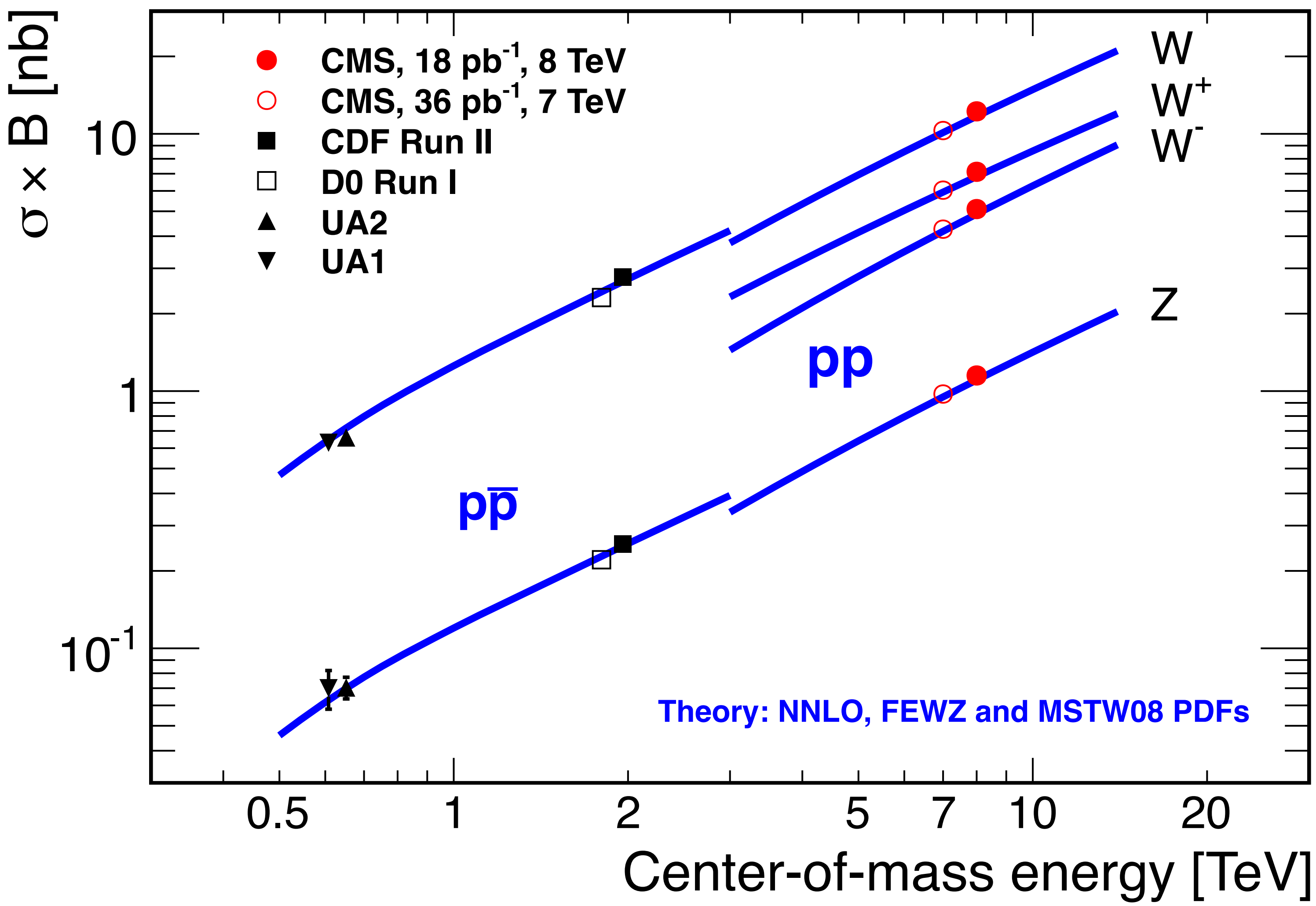




- May 2012 run with greater bunch spacing
  - Average 4 interactions per crossing (vs. 21 for rest of 2012)
  - Int. luminosity of 18.2/pb
- **First inclusive W and Z cross-section measurement at 8 TeV**

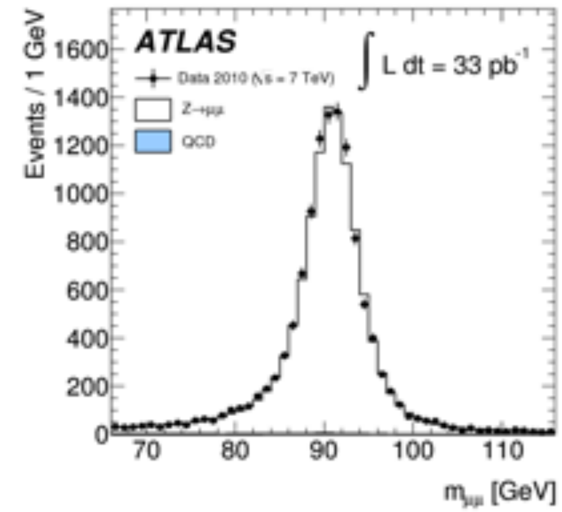


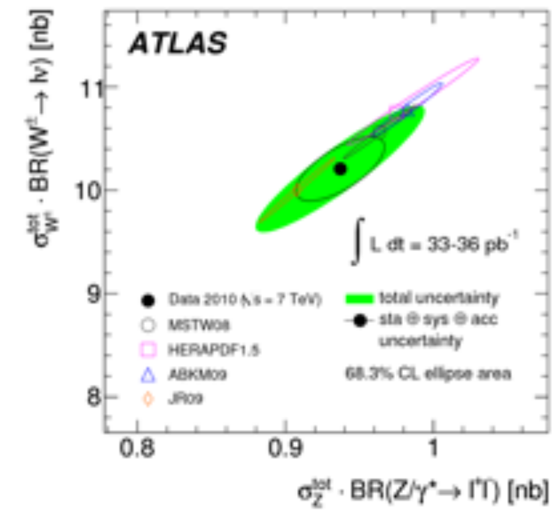

PRL **112**, 191802 (2014)

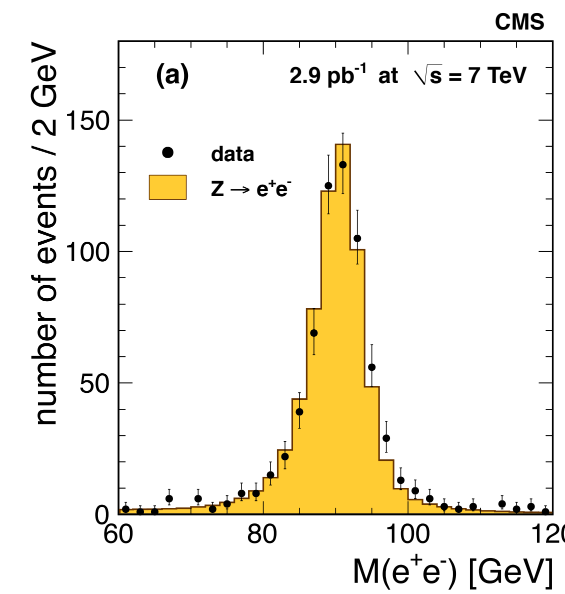
# Hadron collider W and Z cross sections as √s

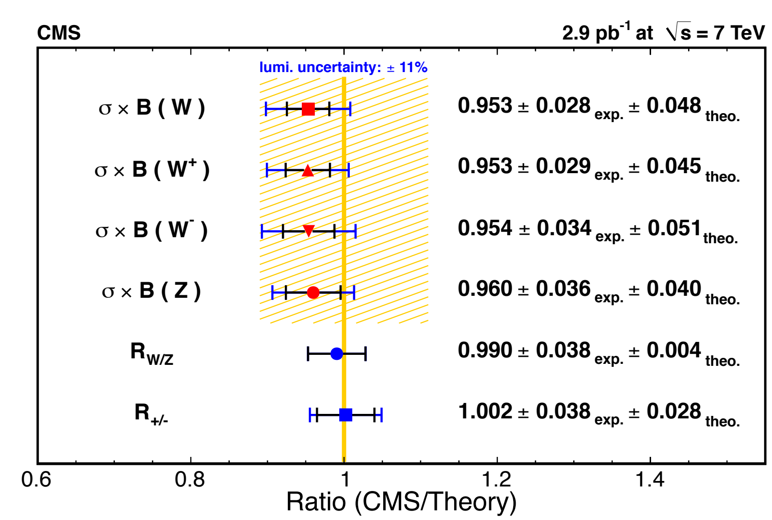



## 7 TeV



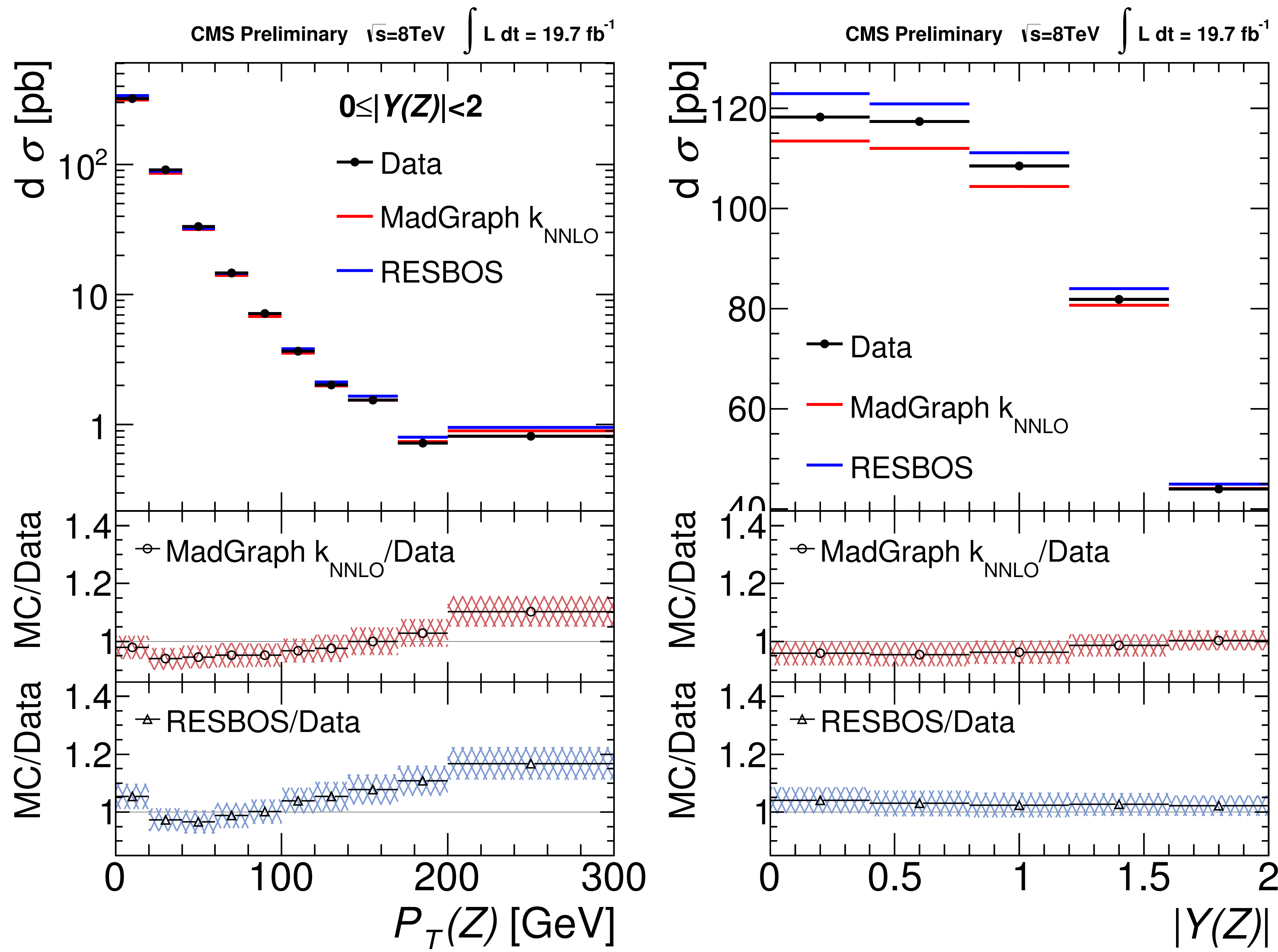




- Hadron collider W/Z cross-sections measured as predicted at 0.6, 1.8, 1.96, 7, and 8 TeV
  - Looking forward to 13-14 TeV!

# $d^2\sigma/[dP_T(Z)d|Y(Z)|]$

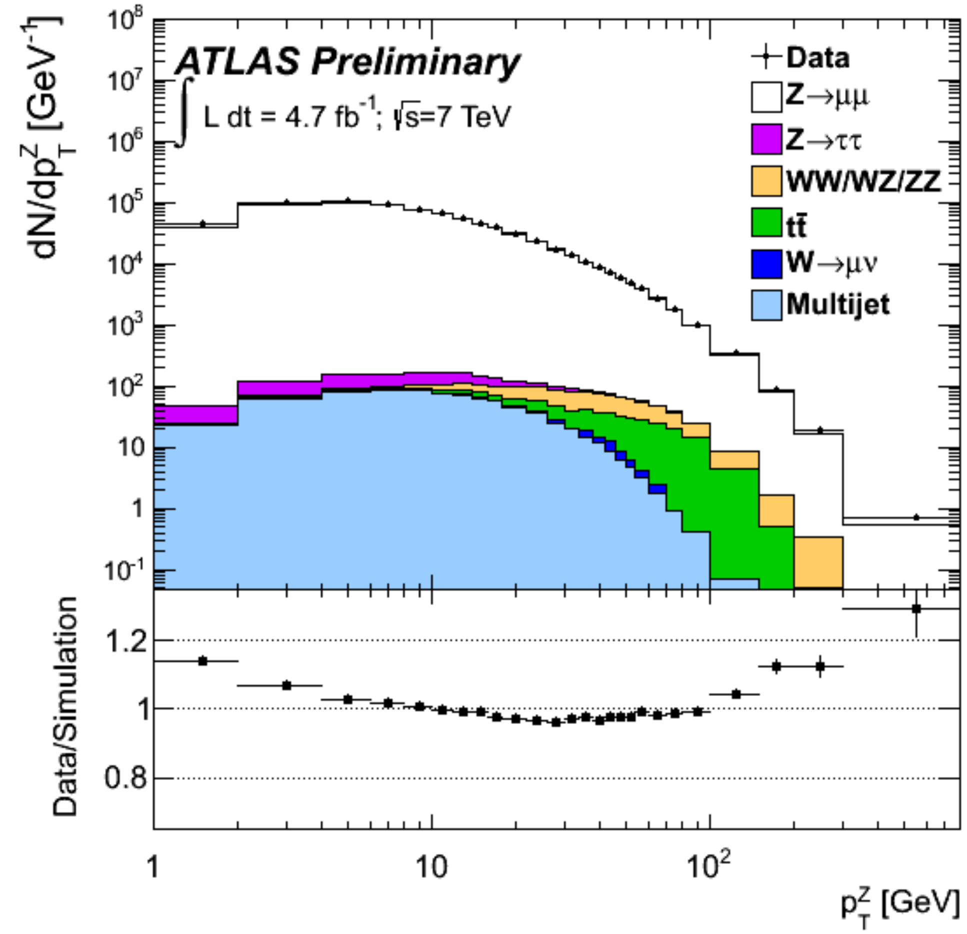
- Explore σ(Z) in high granularity up to high $p_T$
  - **Full 8 TeV dataset**
  - 10 bins in $p_T(Z)$
  - 8 bins in Y(Z)
- Test of QCD dynamics
  - Sensitive to gluon PDF
- Compare to Madgraph +Pythia and RESBOS
  - Shape not well-predicted at high $p_T(Z)$

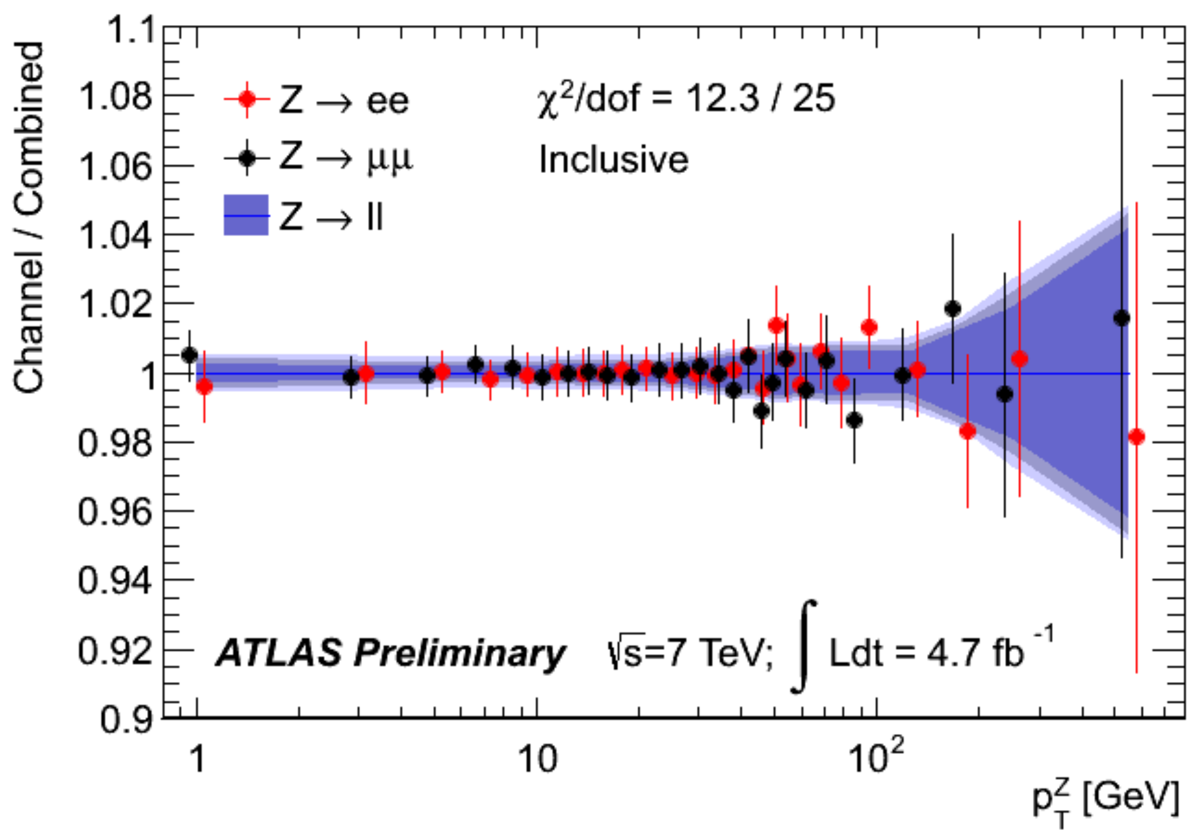


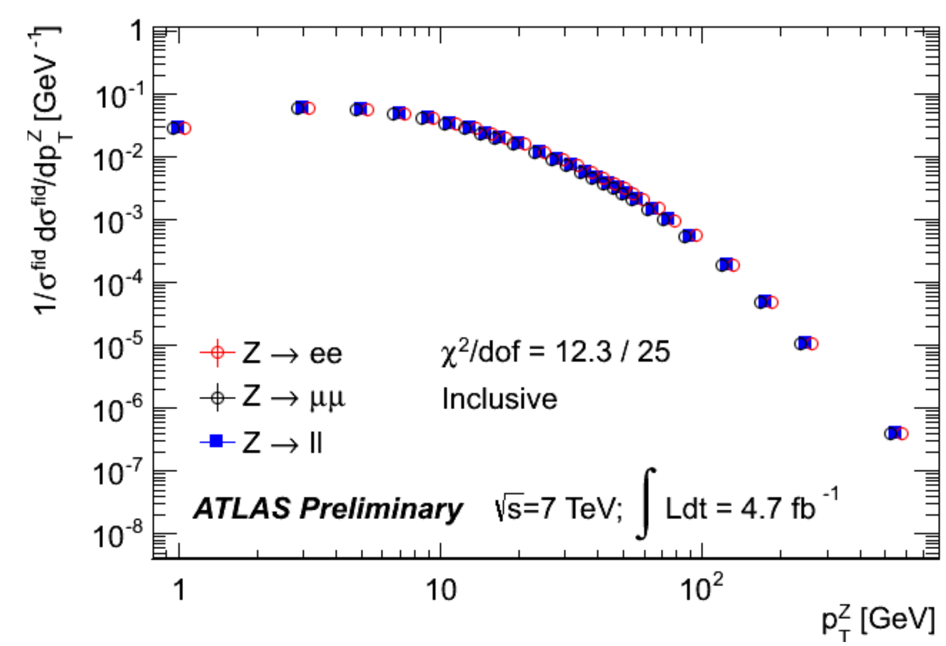

CMS PAS SMP-13-013

# Z/γ* $p_T$ measurement

- Essential for tuning model in W mass measurement
- $p_{T,l}$ > 20 GeV, 66 < $m_{ll}$ < 116 GeV, $|\eta|$ < 2.4
- **~0.5%** precision up to $p_T$(Z) ~ 30 GeV



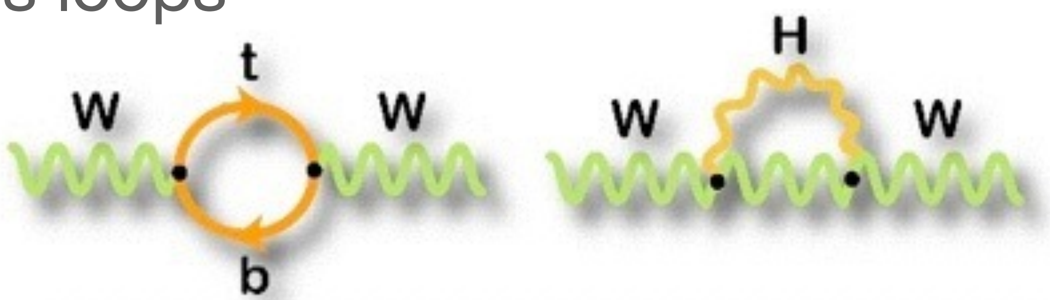
# Direct W Boson Mass Measurements

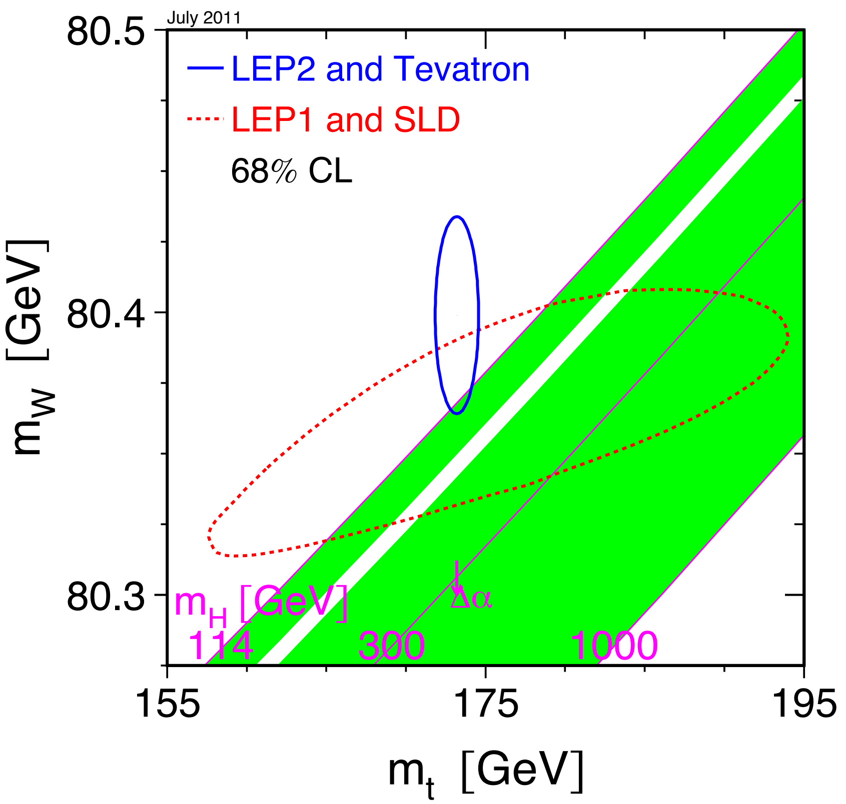
# Measuring the W boson mass

- Electroweak sector of the standard model (SM) relates $m_W$ to well-measured constants

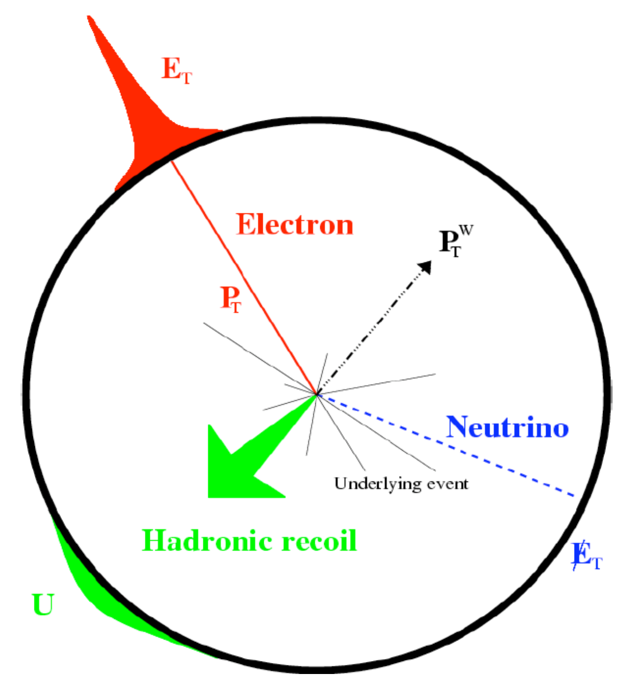
$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)} \qquad \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

- Radiative corrections *Δr* dominated by top and Higgs loops



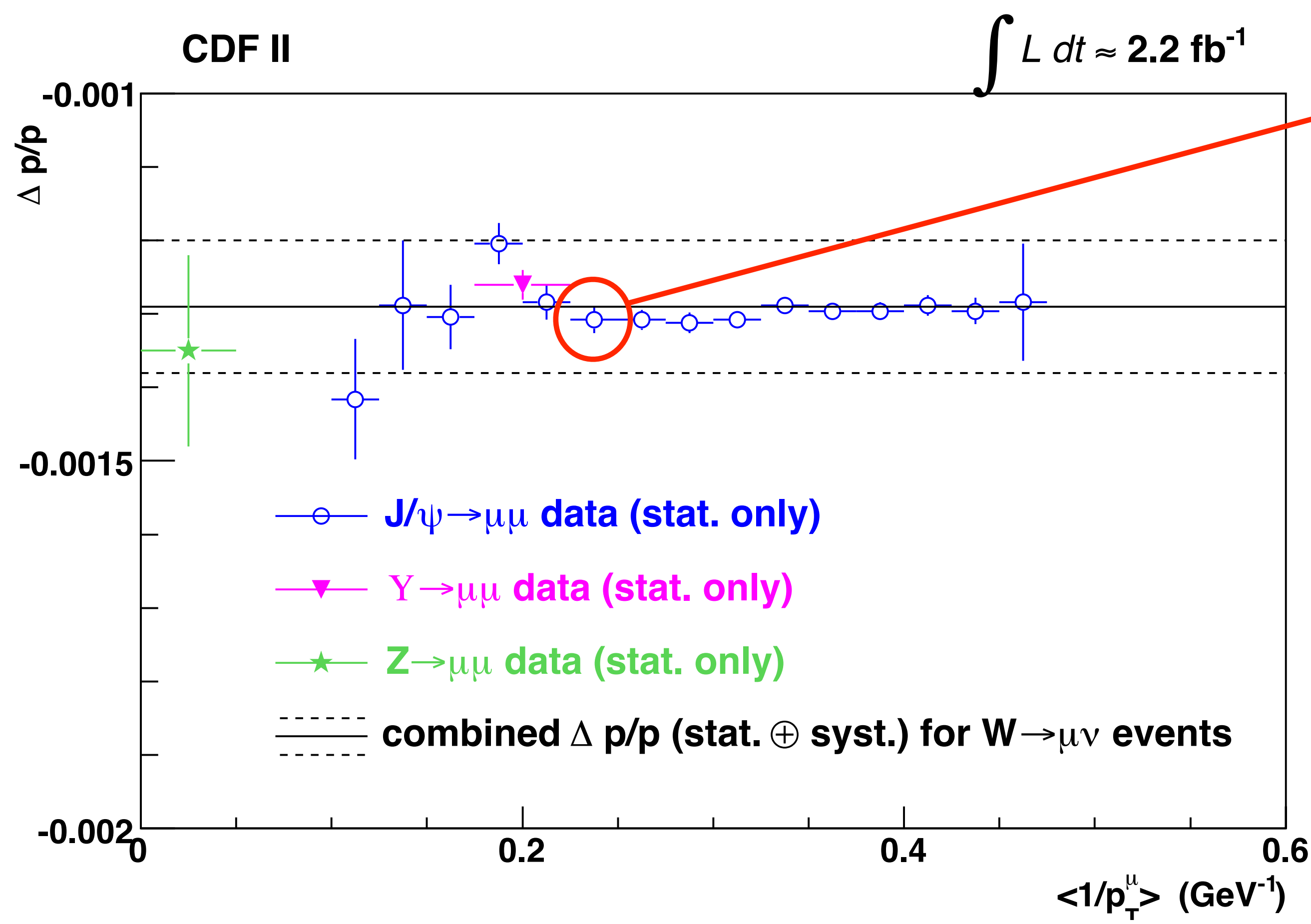



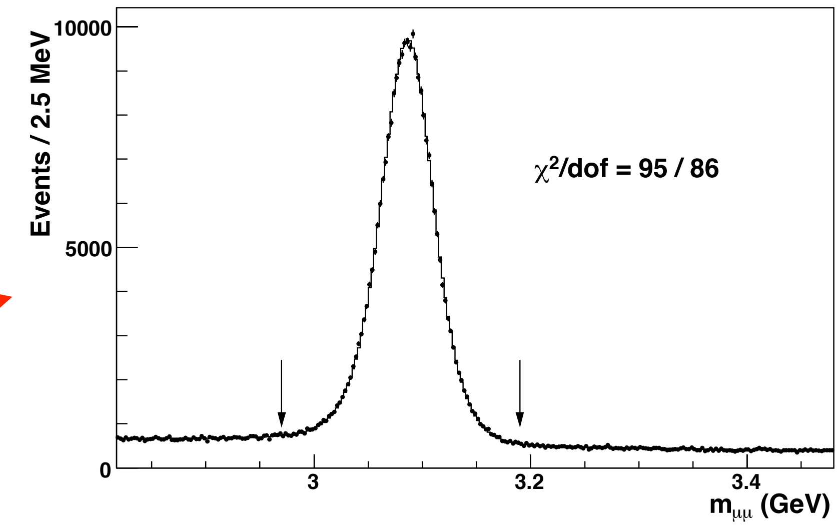

- Precision measurements in ***$m_W$*** and ***$m_{top}$*** tell us if the Higgs is SM or not
- Measuring requires precise measurement of Lepton $p_T$ and transverse hadronic recoil (infer neutrino energy)
- Develop parametrized detector simulation to model detector effects and underlying physics
    - Tune using data

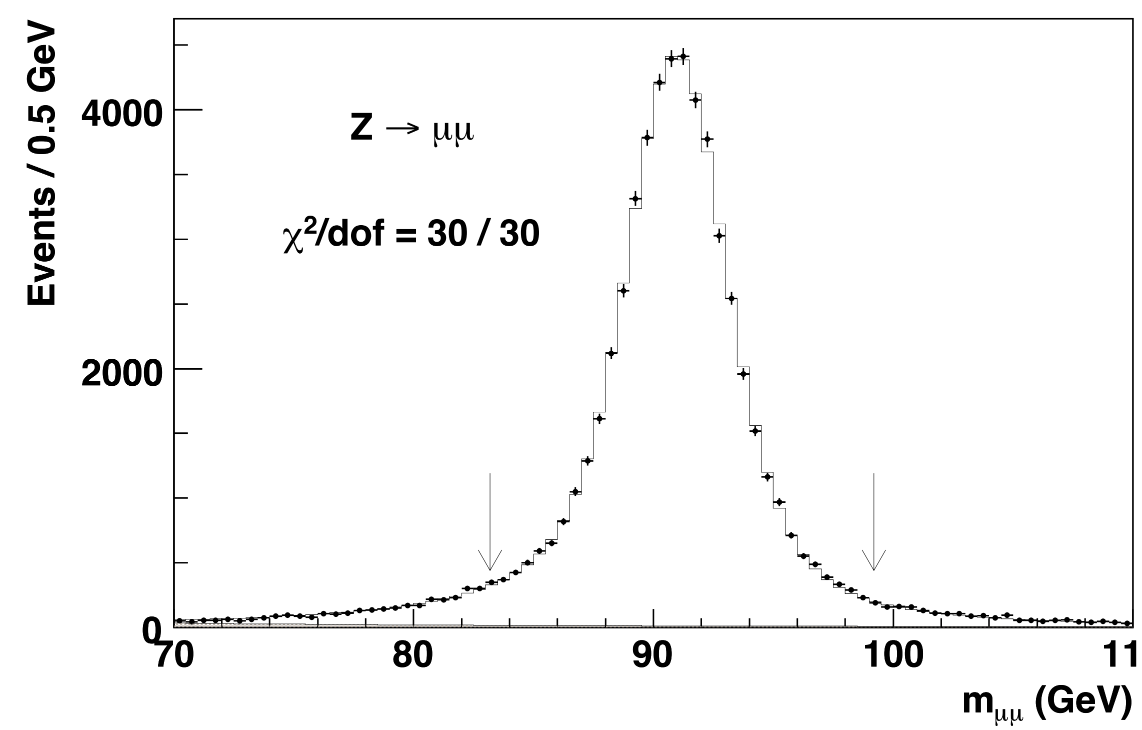


# W mass: track momentum scale

- Foundation of CDF analysis is track $p_T$ measurement with drift chamber (COT)
- Perform alignment using cosmic ray data: ~50μm→~5μm residual
- Calibrate scale using large sample of dimuon resonances (J/ψ, Υ, Z)
  - Span a large range of $p_T$
  - Flatness is a test of dE/dx modeling
  - Final scale error of $9\times10^{-5}$: $\Delta M_W$ = 7 MeV
- Confirm by **measuring $M_Z$**. Add as further constraint.



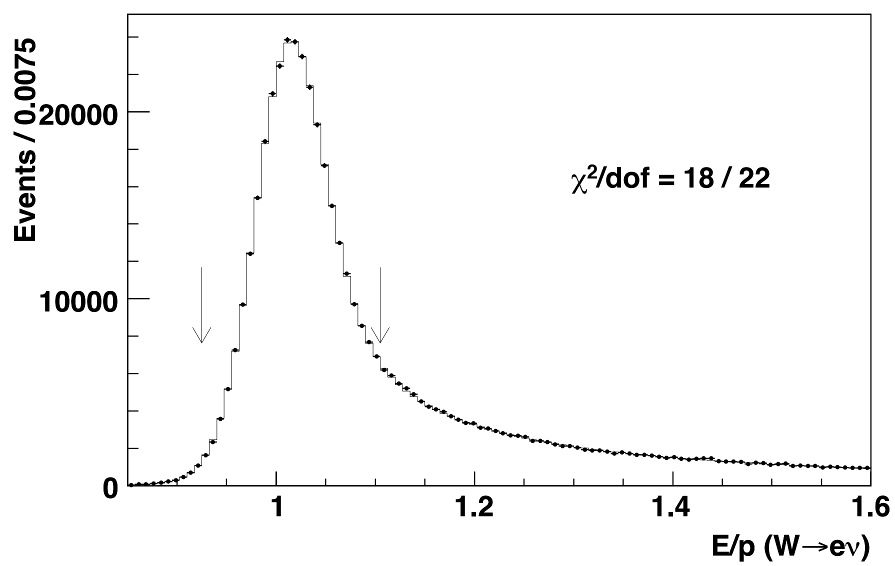



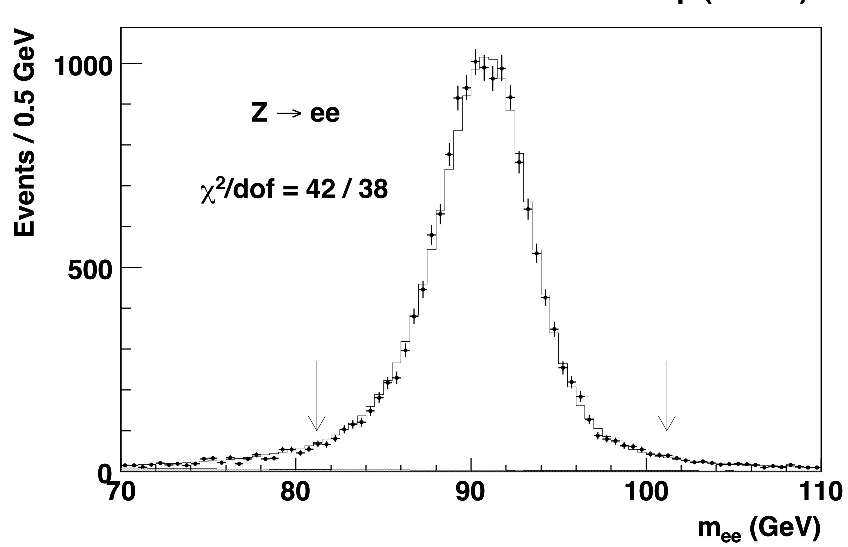



# W mass: calorimeter energy scale

## CDF

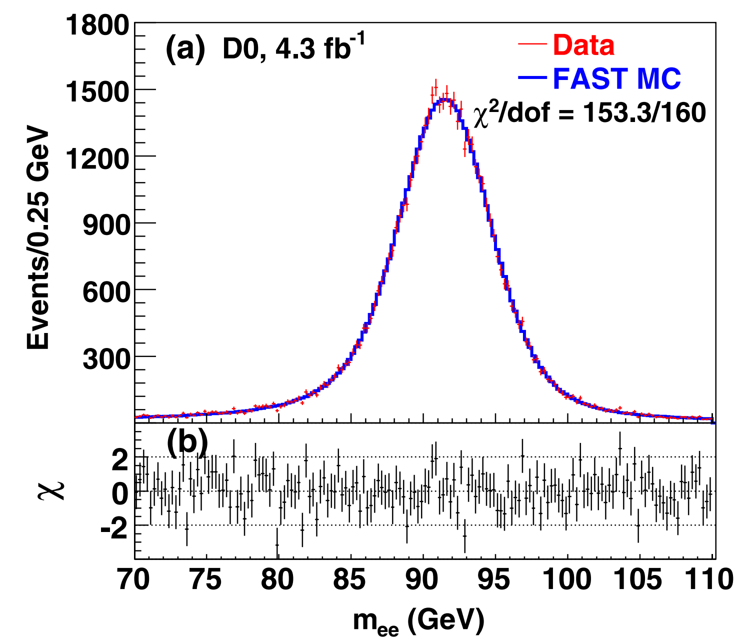
- Apply calibrated p-scale and set EM scale using *E/p* of *W* and *Z* events
  - Overall scale from peak
  - Radiative tail used to tune material model
- Confirm by measuring $M_Z$

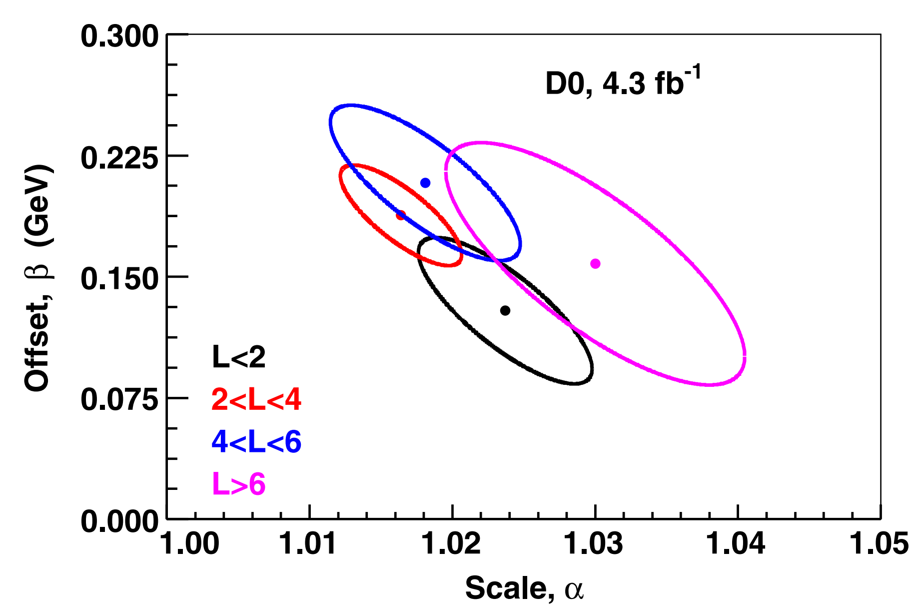



## DØ

- Use $Z \rightarrow ee$ events and LEP $M_Z$ to calibrate scale
- Use subsamples to calibrate material model and response to pileup



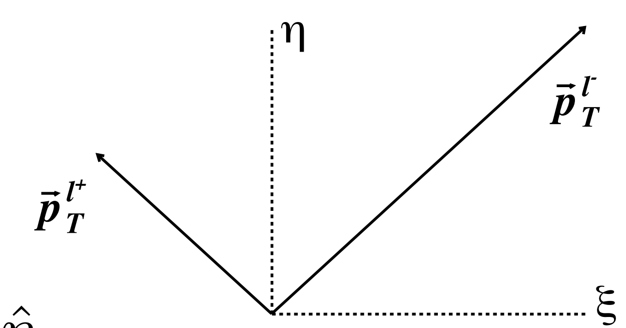

$E_{meas} = \alpha E_{true} + \beta$

Z subsamples of inst. L [*36e30]

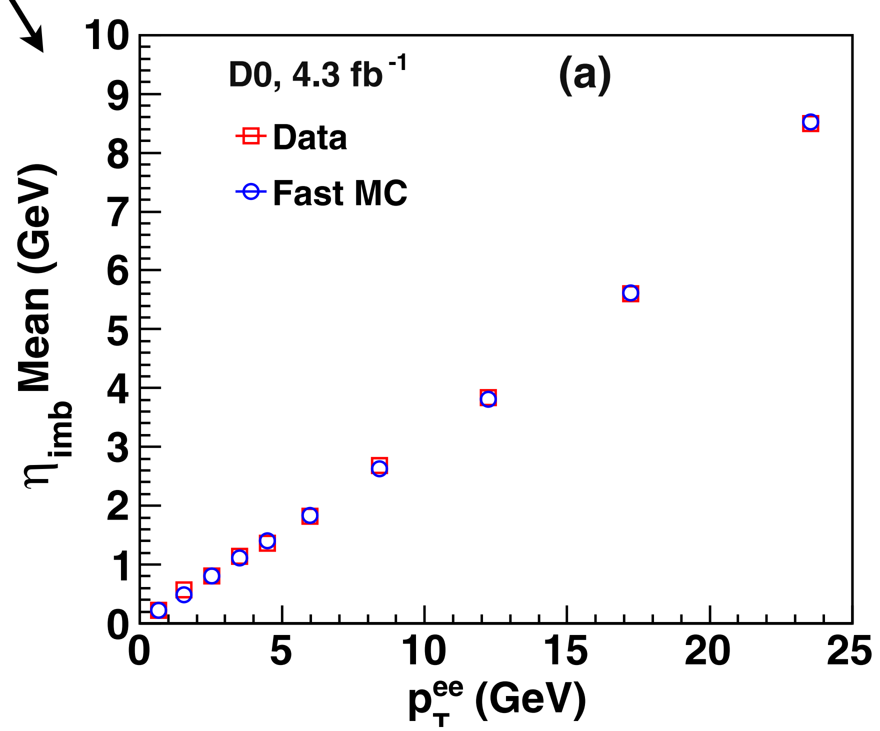
# W mass: recoil calibration

- Measured recoil: 1) hard recoil from hadronic activity in W/Z event, 2) underlying event/spectator interaction energy
- Tune using Z and minimum-bias data
- Validate using measured recoil in W events

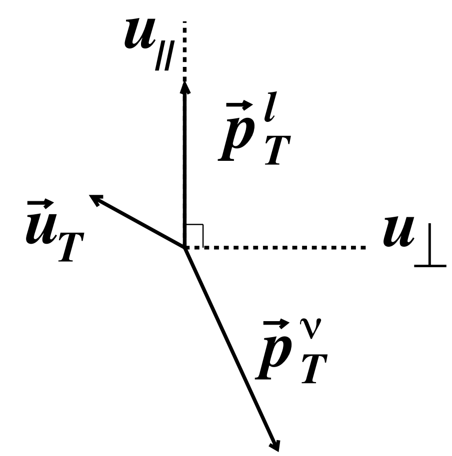
## Tuning with Z→ll




$(\vec{p}_T^{Z} + \vec{u}_T) \cdot \hat{\eta}$




## Validating with W→lν

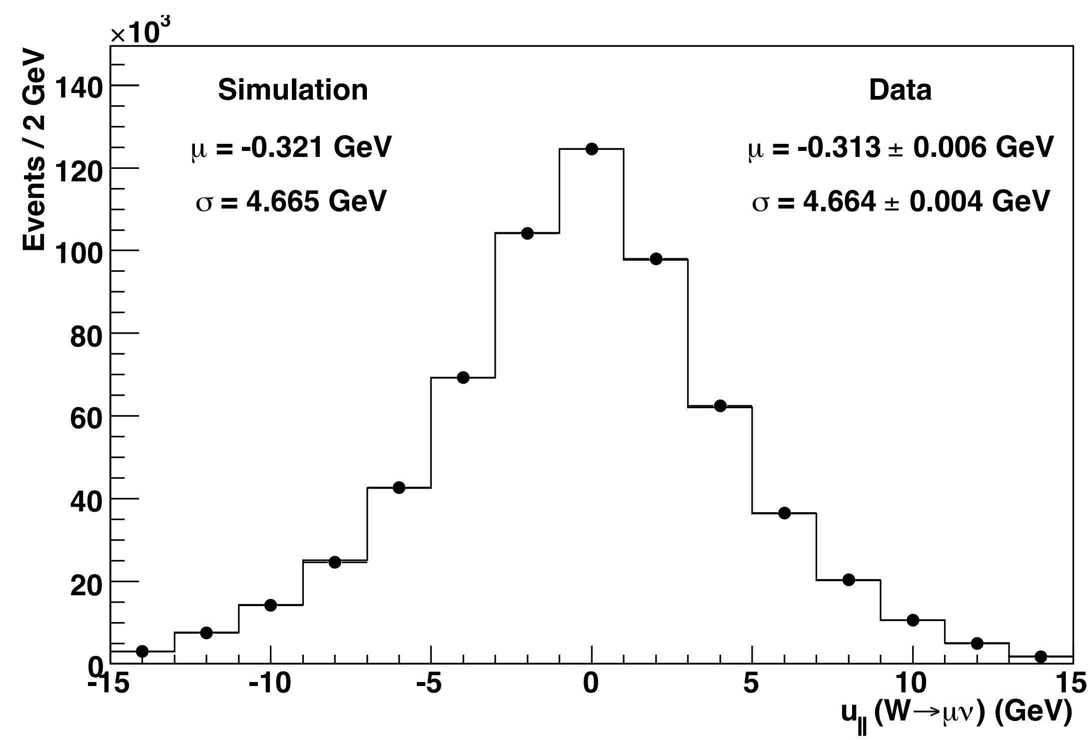



*for $u \ll p_T^l$ :*

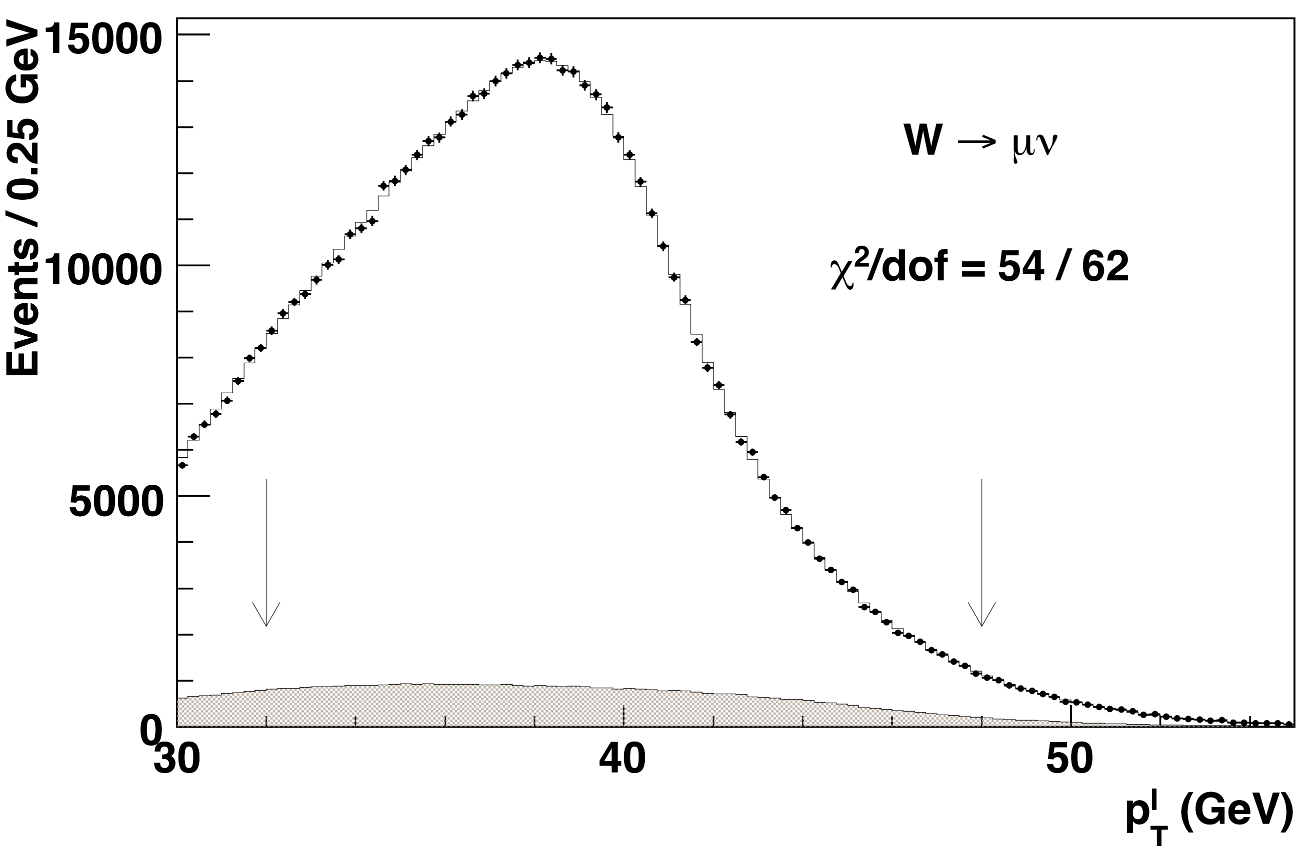
$m_T \approx 2p_T^l + u_{||}$

$p_T^\nu \approx 2p_T^l + 2u_{||}$

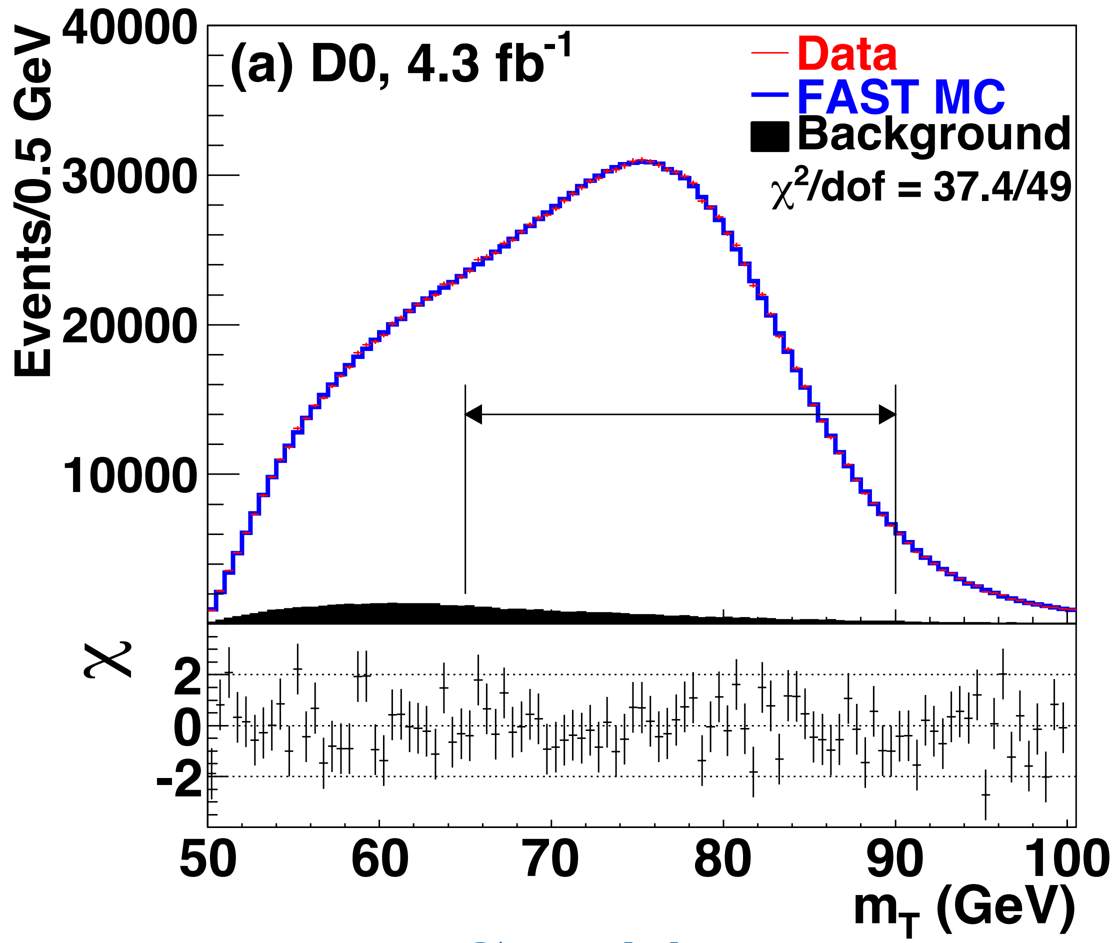
mis-modeled $u_{||}$ directly biases measured $M_W$



# W mass: results




**CDF $p_T(\mu)$ fit**




**DØ $m_T(e)$ fit**

- Fits performed to $m_T$, $p_T^l$, $p_T^\nu$
- Combine all three in both e and μ channels (CDF) and $p_T^l$, $m_T$ in e channel (DØ), taking into account correlations

***$M_W$* = 80387 ± 19 MeV (CDF, 2.2 fb$^{-1}$)**

PRD **89**, 072003 (2014)

***$M_W$* = 80367 ± 26 MeV (DØ, 4.3 fb$^{-1}$)**

***$M_W$* = 80375 ± 23 MeV (DØ, 4.3+1.0 fb$^{-1}$)**

PRD **89**, 012005 (2014)

# W mass: uncertainties

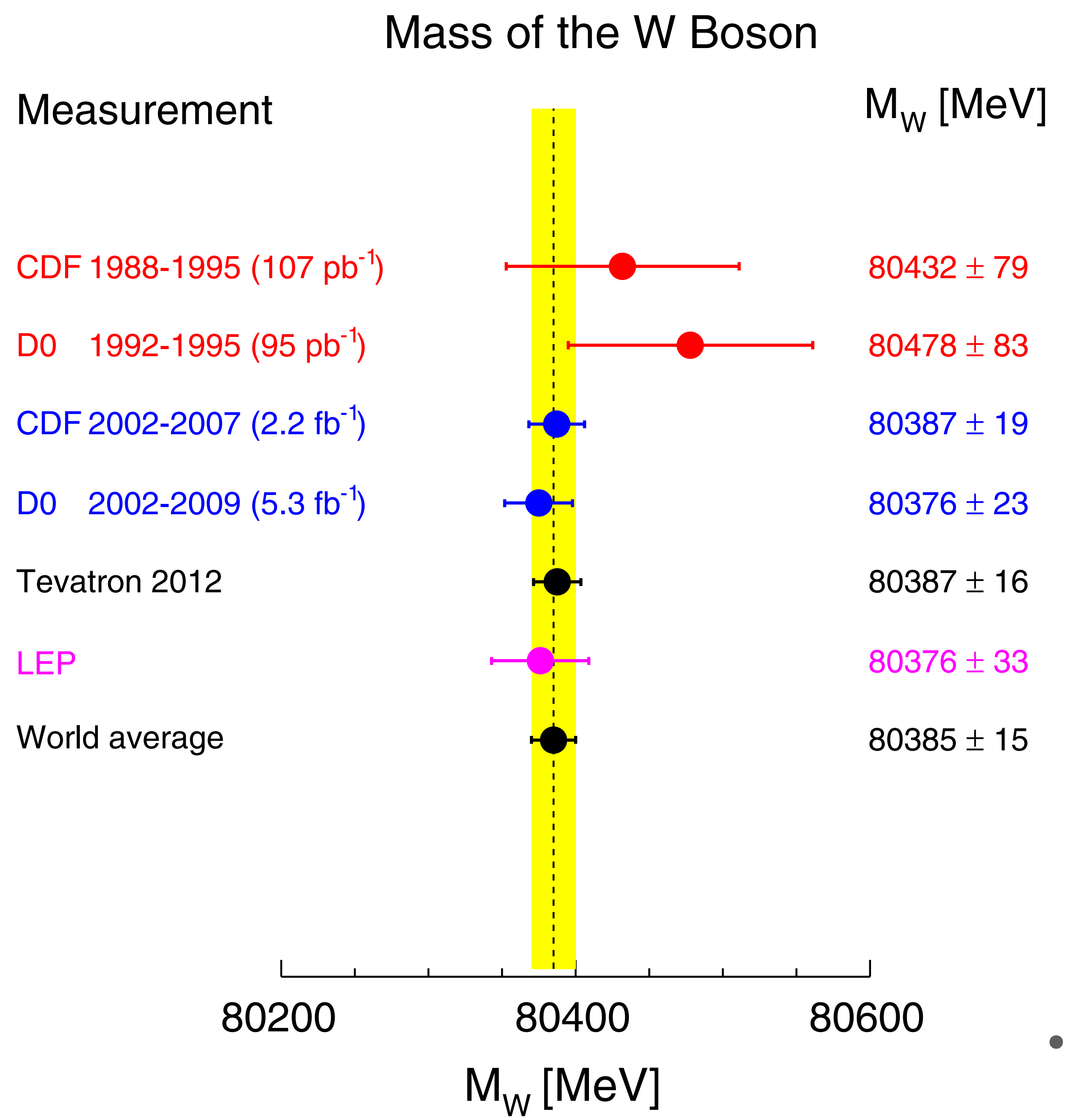
*Uncertainties on transverse mass fits for $M_W$ [MeV]*

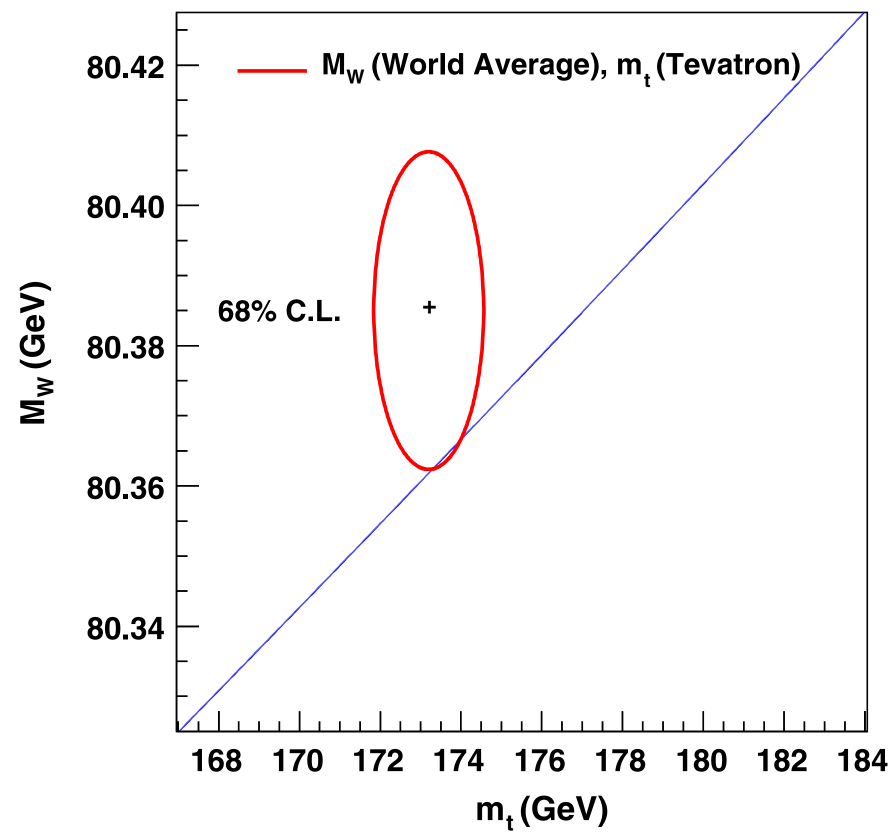
| **Source** | **CDF** | **CDF** | **DØ** |
|---|---|---|---|
| Lepton energy scale | 7 | 10 | 17 |
| Lepton energy resolution | 1 | 4 | 2 |
| Recoil model | 9 | 9 | 5 |
| Lepton efficiency | - | - | 1 |
| Backgrounds | 3 | 4 | 2 |
| $p_T$ | 3 | 3 | 2 |
| PDFs | 10 | 10 | 11 |
| QED radiation | 4 | 4 | 7 |
| *Total systematics* | *16* | *18* | *22* |
| W statistics | 16 | 19 | 13 |
| ***Total*** | ***23*** | ***26*** | ***26*** |

Modeling uncertainties (PDFs) beginning to dominate

*c.f.* Lepton scale uncertainty for CDF with 200 $pb^{-1}$ was 30 MeV

# W mass: combination




***$M_W$* = 80385 ± 15 MeV**

PRD **88**, 052018 (2013)

*nb:* 2009 world average
$M_W$ = 80399±**23** MeV

- Analysis being performed with full Tevatron dataset
  - CDF ~ 10 MeV, DØ ~15 MeV total uncertainty projected
- LHC with further PDF constraints— < 10 MeV?

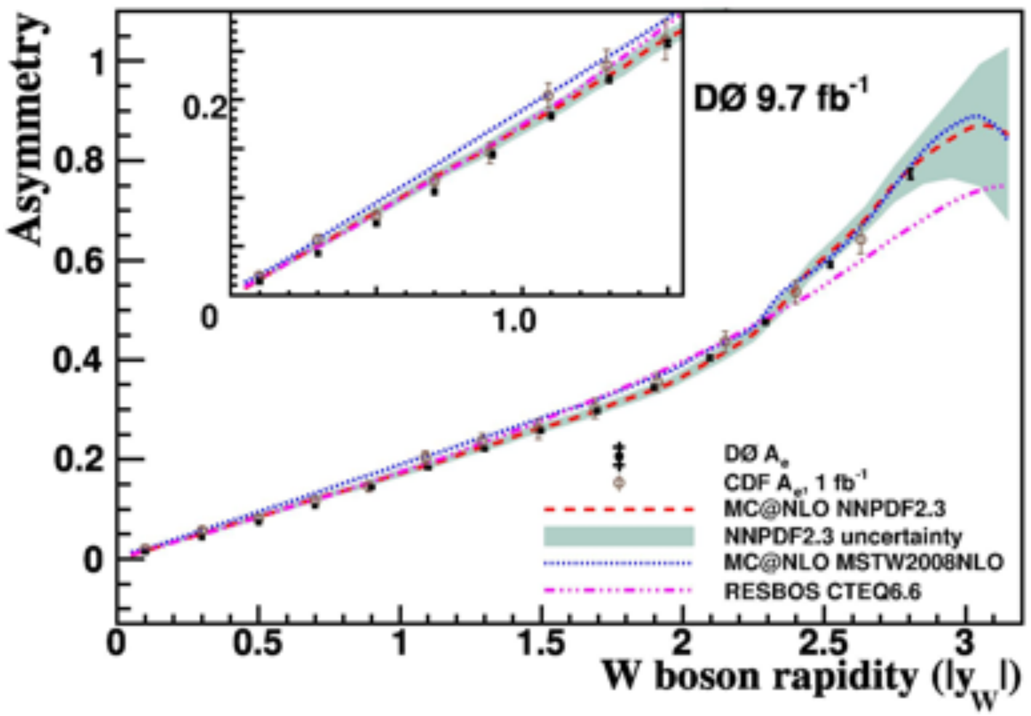
# Asymmetry measurements

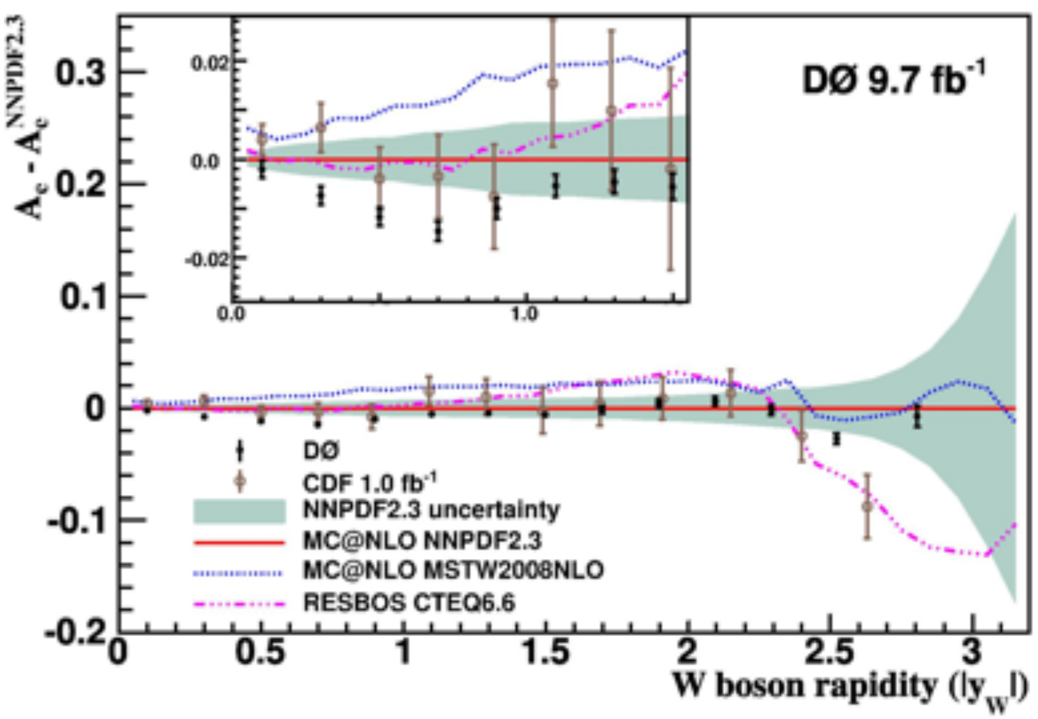
# W boson charge asymmetry

- $W^+$($W^-$) boosted in direction of (anti)proton
- Difference in u, d PDFs results in W charge asymmetry at Tevatron

$$A(y_W) = \frac{d\sigma_{W^+}/dy_W - d\sigma_{W^-}/dy_W}{d\sigma_{W^+}/dy_W + d\sigma_{W^-}/dy_W}.$$

  - No V-A dilution
- DØ measurement uses full dataset in electron channel
  - Use neutrino weighting method [PRD **77**, 111301 (2008)]
- Critical data for improving PDF precision

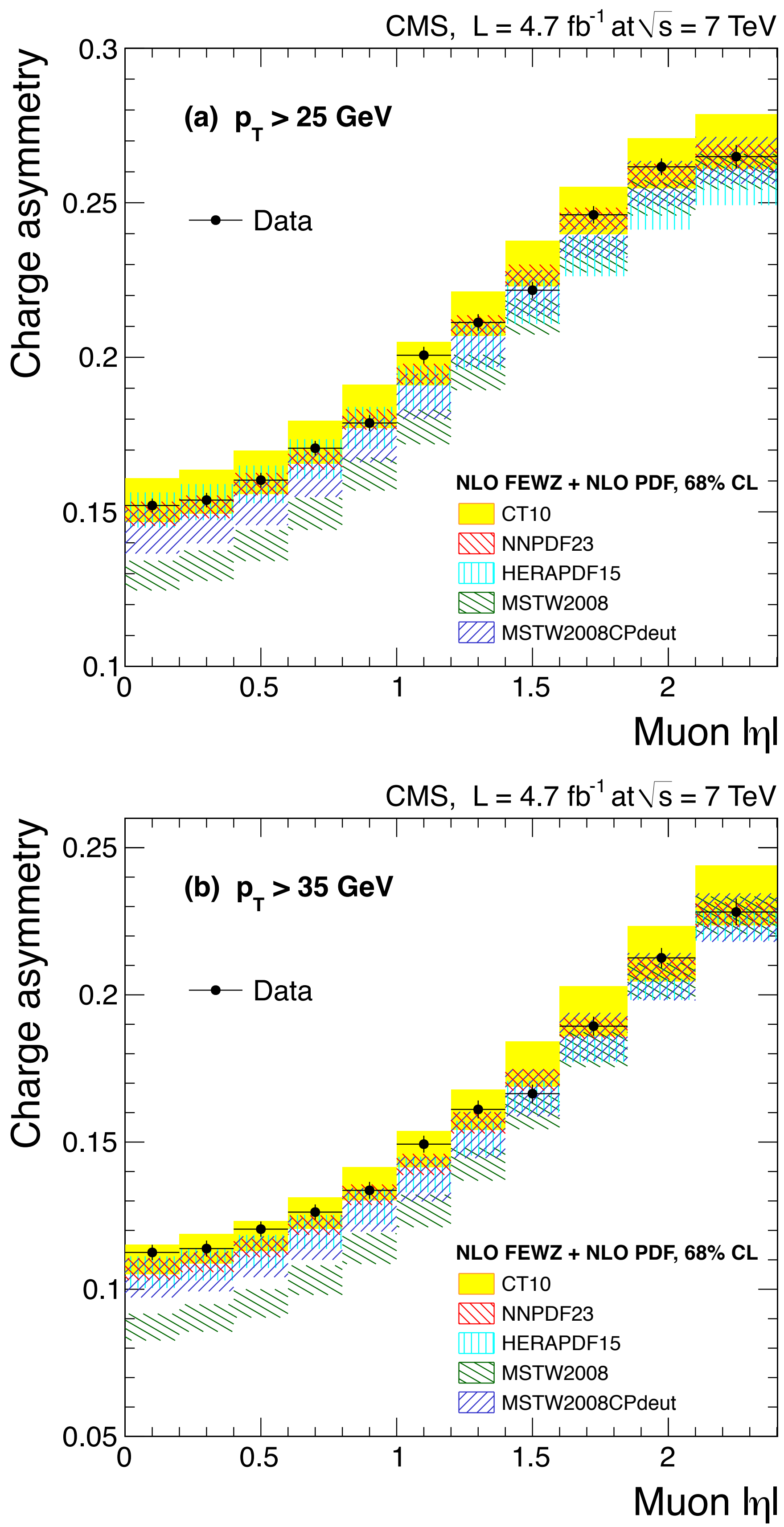



PRL **112**, 151803 (2014)

# Muon charge asymmetry

- Greater $W^+$ production rate than $W^-$ rate at pp colliders
  - Difference can help constrain PDFs
- Use 7 TeV dataset
  - Similar event selection as inclusive W cross-section measurement
- Measure asymmetry in bins of $|\eta|$
- Measure with two different $p_T$ cuts: 25 and 35 GeV
- Compare with predictions using various PDFs




arXiv:1312.6283

# Measuring $\sin^2\theta_W$

- In the SM:

$$\sin\theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

from LEP

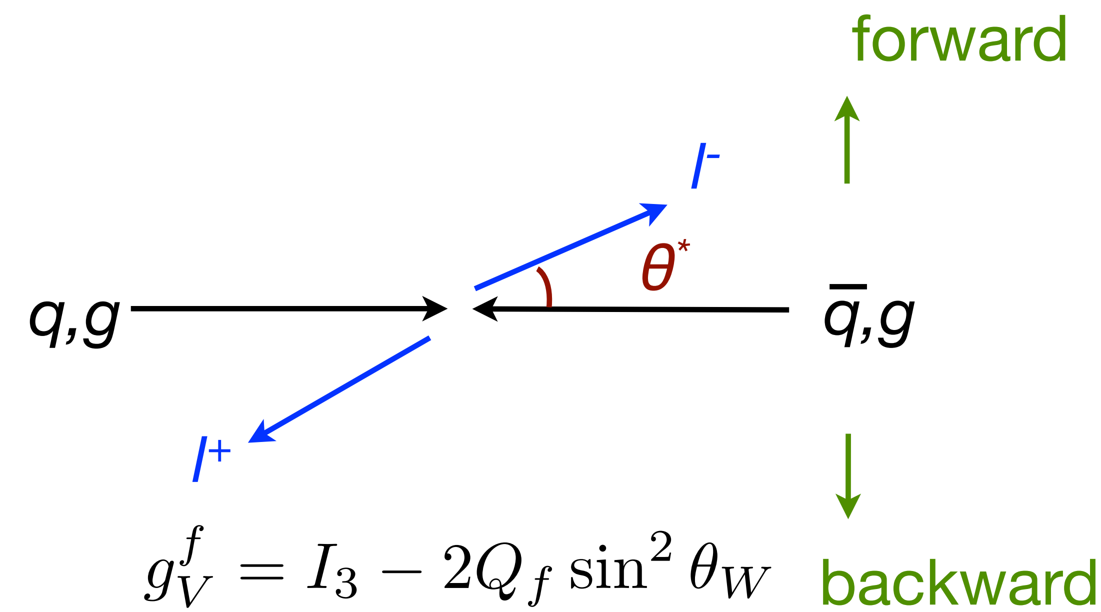
- Measurement of $\sin^2\theta_W$ indirectly measures $M_W$
- Obtain from angular distribution of leptons in Drell-Yan ($Z/\gamma^* \rightarrow l^+l^-$) events

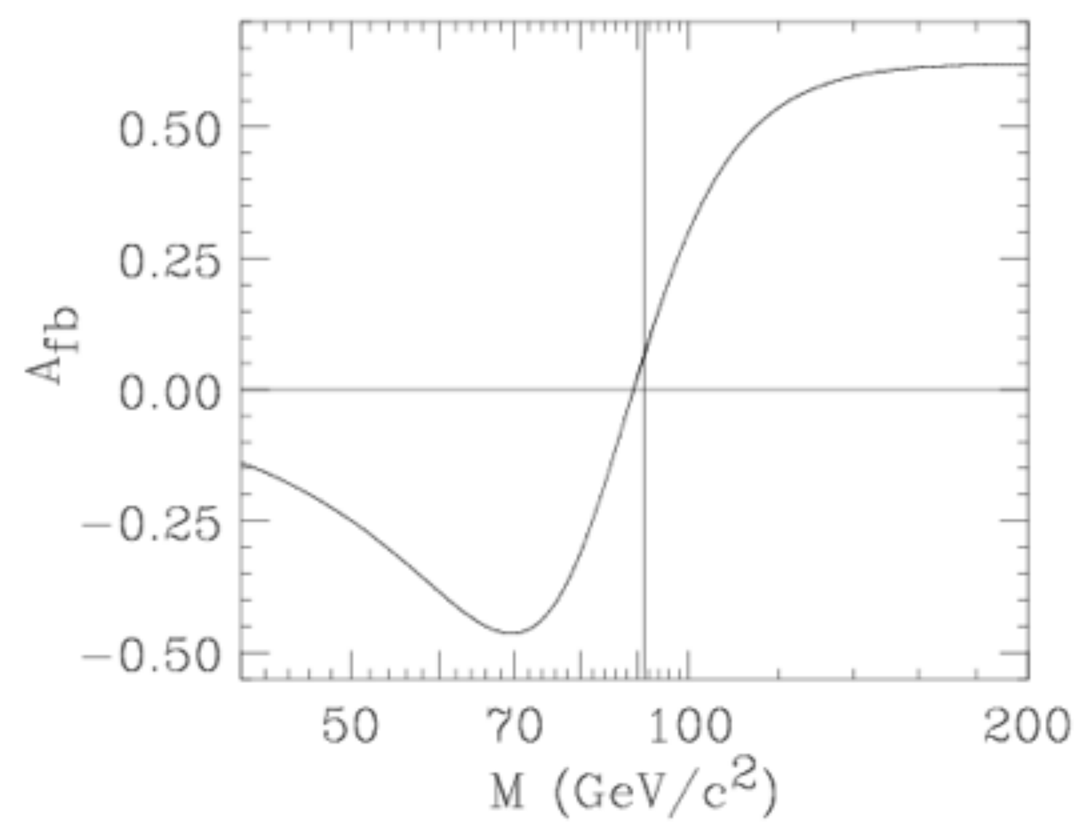
$$\frac{dN}{d\theta} \approx 1 + \cos^2\theta + A_4\cos\theta$$

  - Forward-backward asymmetry

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}A_4$$

- Measure $A_{FB} \rightarrow \sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}}$ (effective $Z$/lepton coupling) $\rightarrow \sin^2\theta_W \rightarrow M_W$



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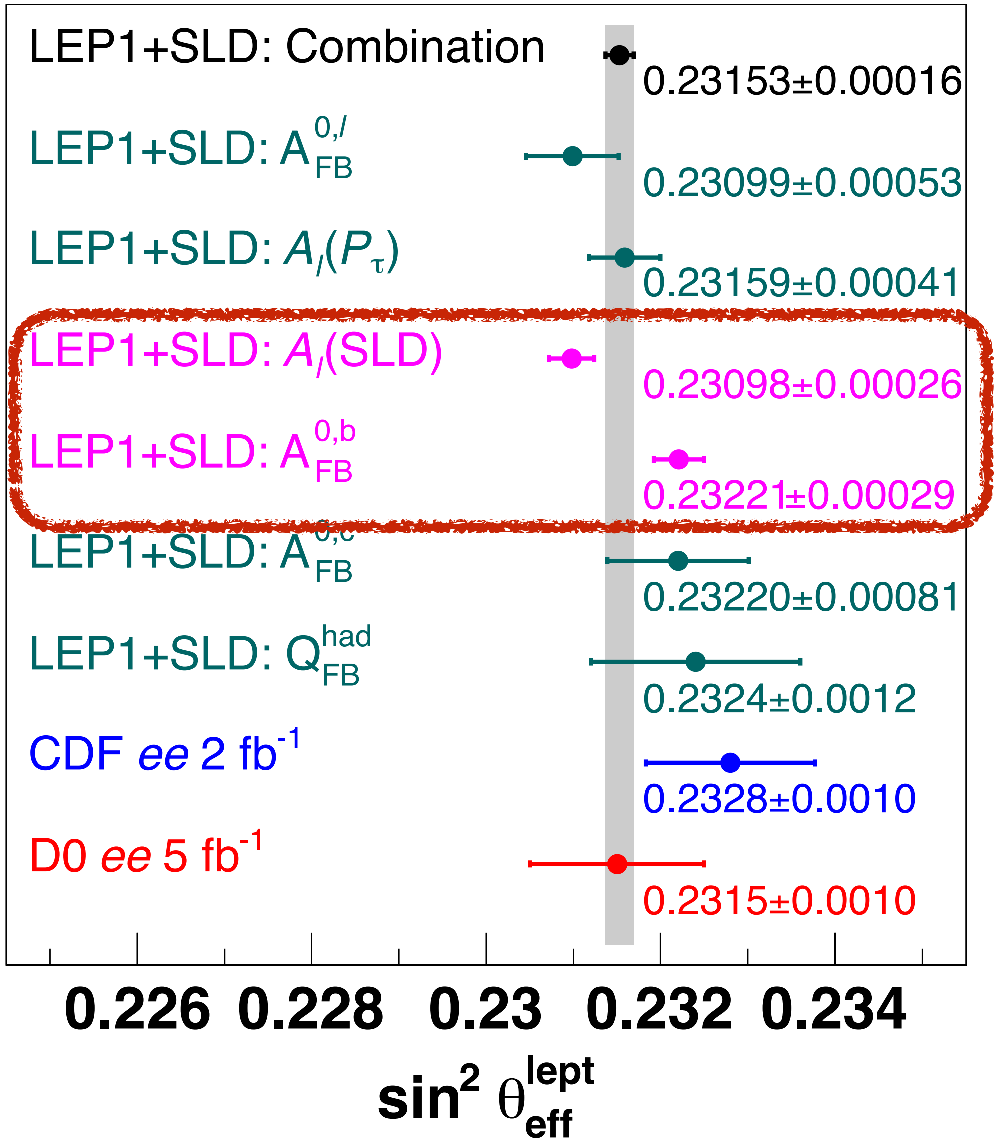
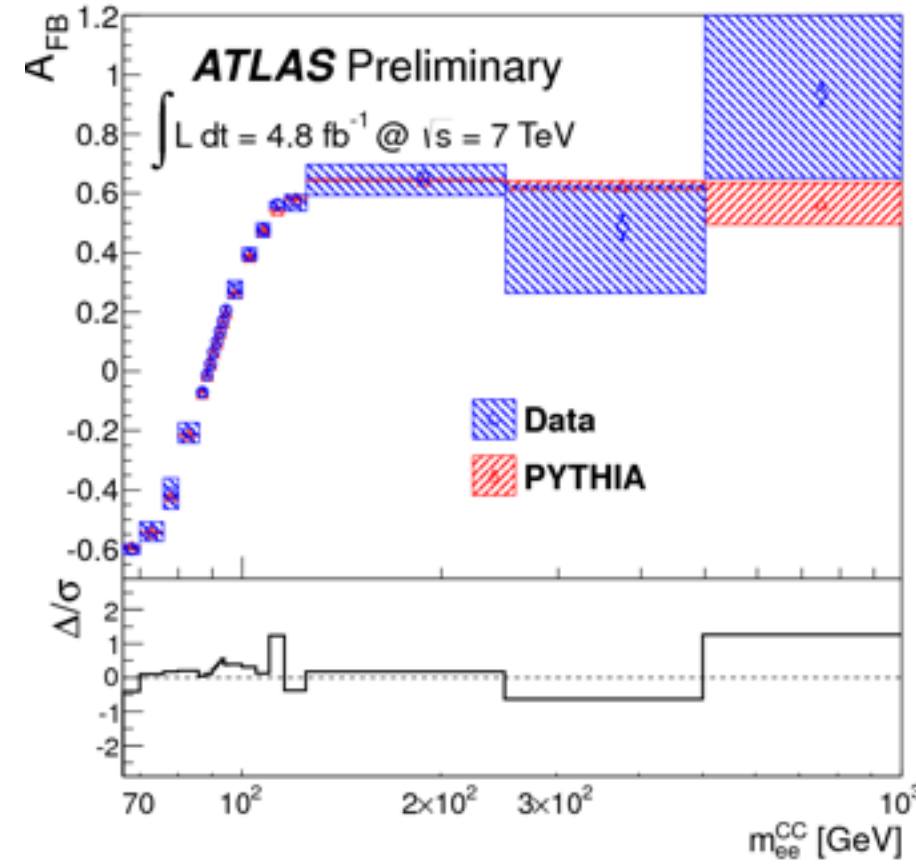


# ATLAS $A_{FB}$ measurement

- ee and μμ measurement using 4.8/fb of 7 TeV data
  - Electron channel split into CC and CF
    - CF includes one electron |η| < 4.9
- Unfold raw $A_{FB}$ to obtain $\sin^2\theta_{eff}$
- Extract each channel (Muon, CC, CF) separately
  - Final result is combined across all three channels



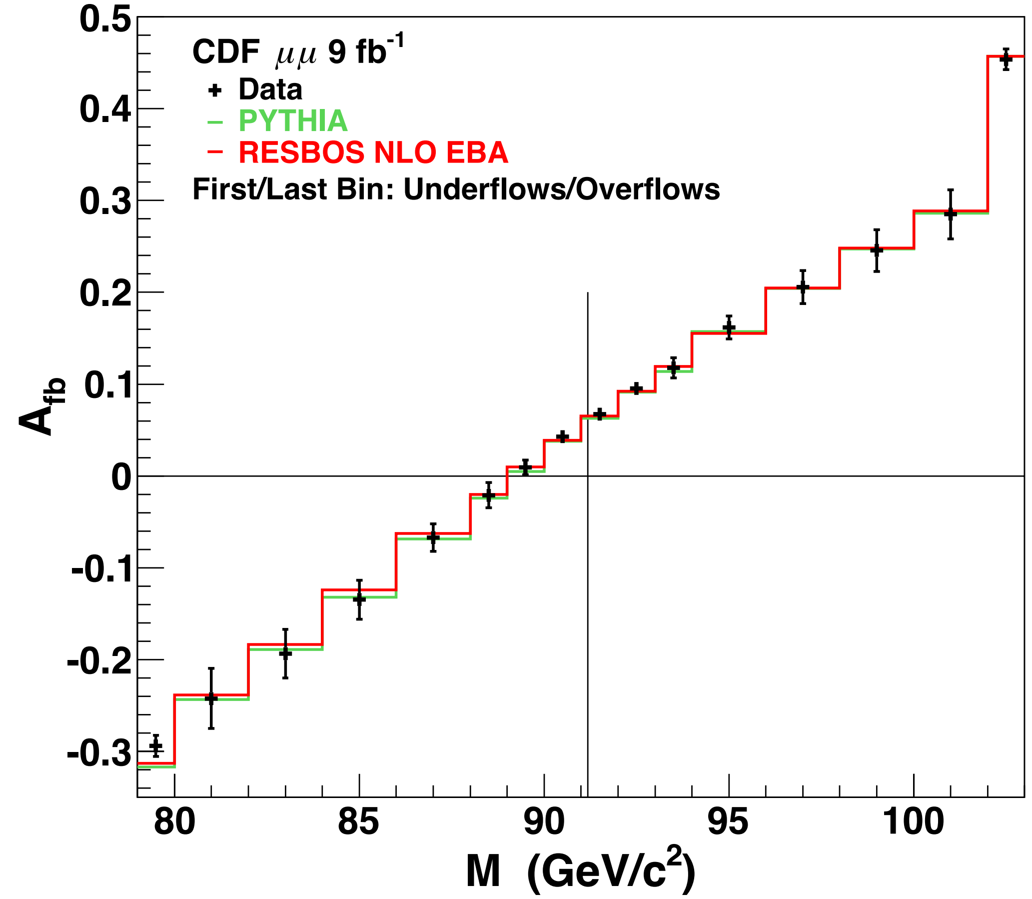

**$\sin\theta_{eff} = 0.2297 \pm 0.0010$**

| Uncertainty source | CC electrons ($10^{-4}$) | CF electrons ($10^{-4}$) | Muons ($10^{-4}$) | Combined ($10^{-4}$) |
|---|---|---|---|---|
| PDF | 9 | 5 | 9 | 7 |
| MC statistics | 9 | 5 | 9 | 4 |
| Electron energy scale | 4 | 6 | – | 4 |
| Electron energy smearing | 4 | 5 | – | 3 |
| Muon energy scale | – | – | 5 | 2 |
| Higher-order corrections | 3 | 1 | 3 | 2 |
| Other sources | 1 | 1 | 2 | 2 |

ATLAS-CONF-2013-043

# CDF $A_{FB}$ (μμ) measurement

- Measured using muon pairs (central)
  - 10 different topologies depending on muon subdetector
  - Use event-weighting method to contend with 10 different $\varepsilon A$ [EPJ C **72**, 2194 (2012)]
- Extract mixing angle from raw $A_{FB}$



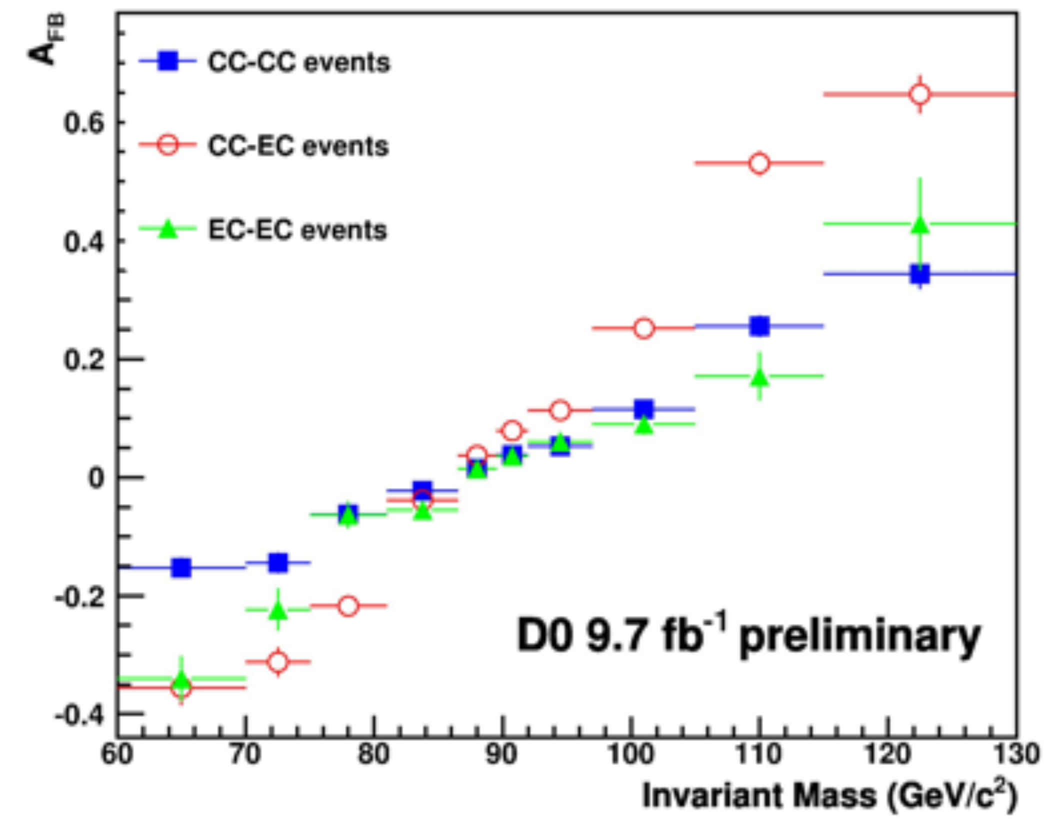

$$\sin^2\theta_W = 0.2233 \pm 0.0010$$
$$\sin^2\theta_{eff} = 0.2315 \pm 0.0010$$

| Source | $\sin^2\theta^{\rm lept}_{\rm eff}$ | $\sin^2\theta_W$ |
|---|---|---|
| Momentum scale | $\pm 0.00005$ | $\pm 0.00005$ |
| Backgrounds | $\pm 0.00010$ | $\pm 0.00010$ |
| QCD scales | $\pm 0.00003$ | $\pm 0.00003$ |
| CT10 PDFs | $\pm 0.00037$ | $\pm 0.00036$ |
| EBA | $\pm 0.00012$ | $\pm 0.00012$ |

PRD **89**, 072005 (2014)

# DØ $A_{FB}$ (ee) measurement

- Extend η coverage of selection, include EC-EC (endcap) events
  - ~85% more statistics than scaling 5/fb to 9.7/fb
- Implement new energy scale calibration
  - Calibrate E as a function of $L_{inst}$
  - Then calibrate as function of $\eta_{det}$
- Extract mixing angle from raw $A_{FB}$

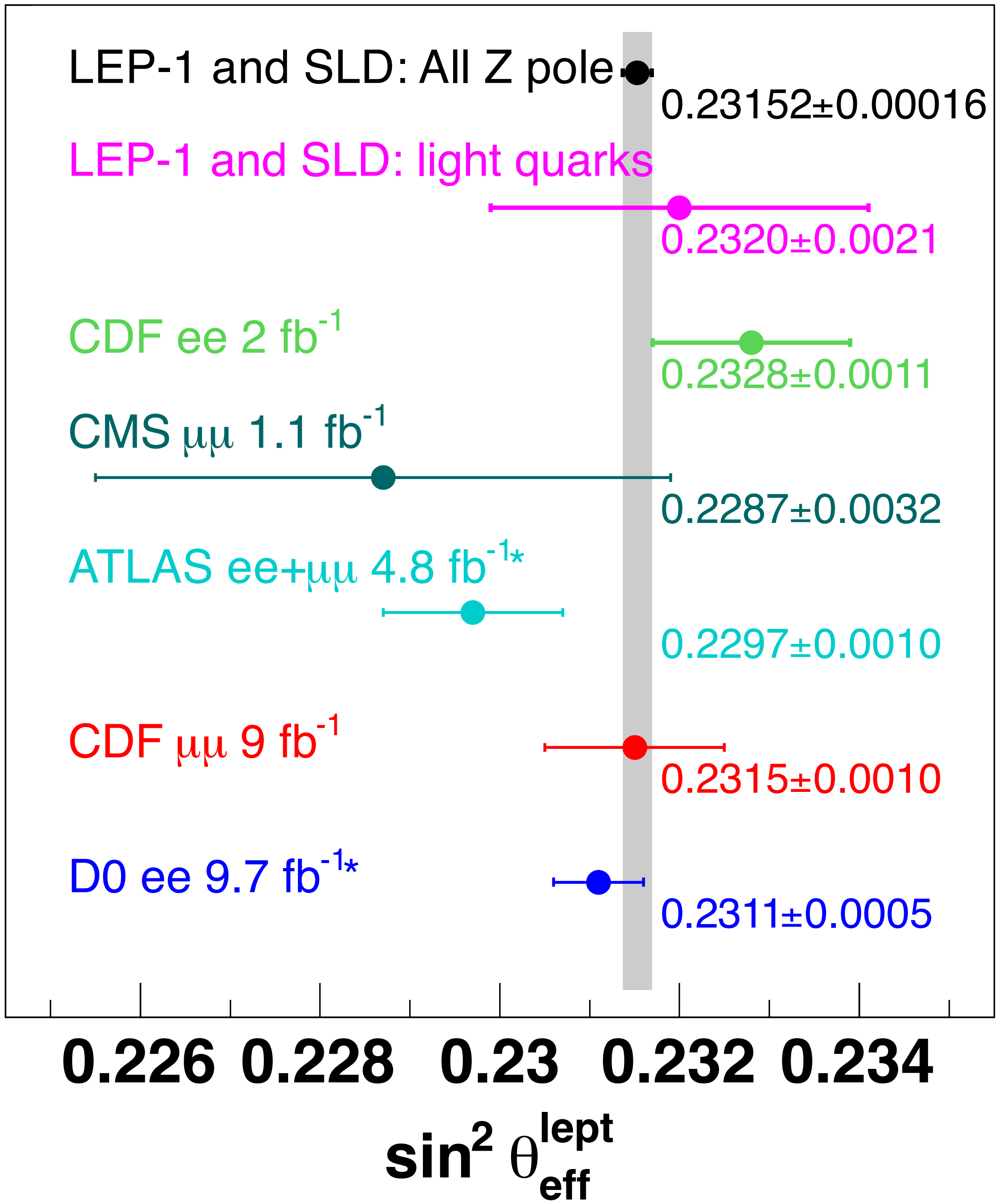



**$\sin^2\theta_W = 0.23098 \pm 0.00044$**
**$\sin^2\theta_{eff} = 0.23106 \pm 0.00053$**

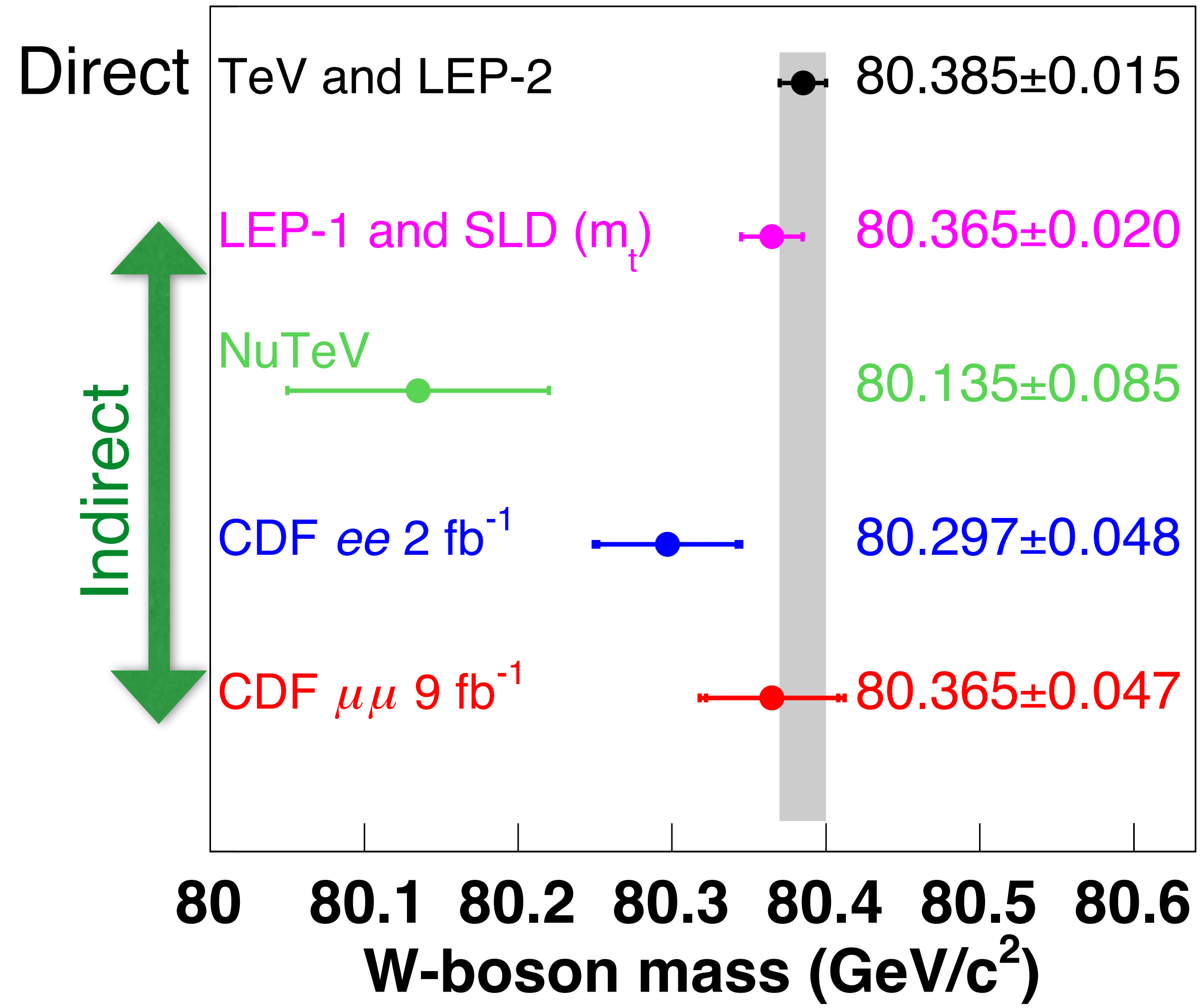
| $\sin^2\theta_W$ | **0.23098** |
|---|---|
| statistical unc. | 0.00042 |
| Energy scale | 0.00012 |
| Energy smear | 0.000018 |
| Background | 0.000008 |
| Charge misID | 0.000030 |
| Electron ID | 0.000066 |
| Total systematic unc. | 0.00014 |
| total unc. | 0.00044 |

DØ note 6426-conf

# $\sin^2\theta_W$ summary




*preliminary




Combined CDF+D0 indirect $M_W$ in both channels will have **~20 MeV** precision

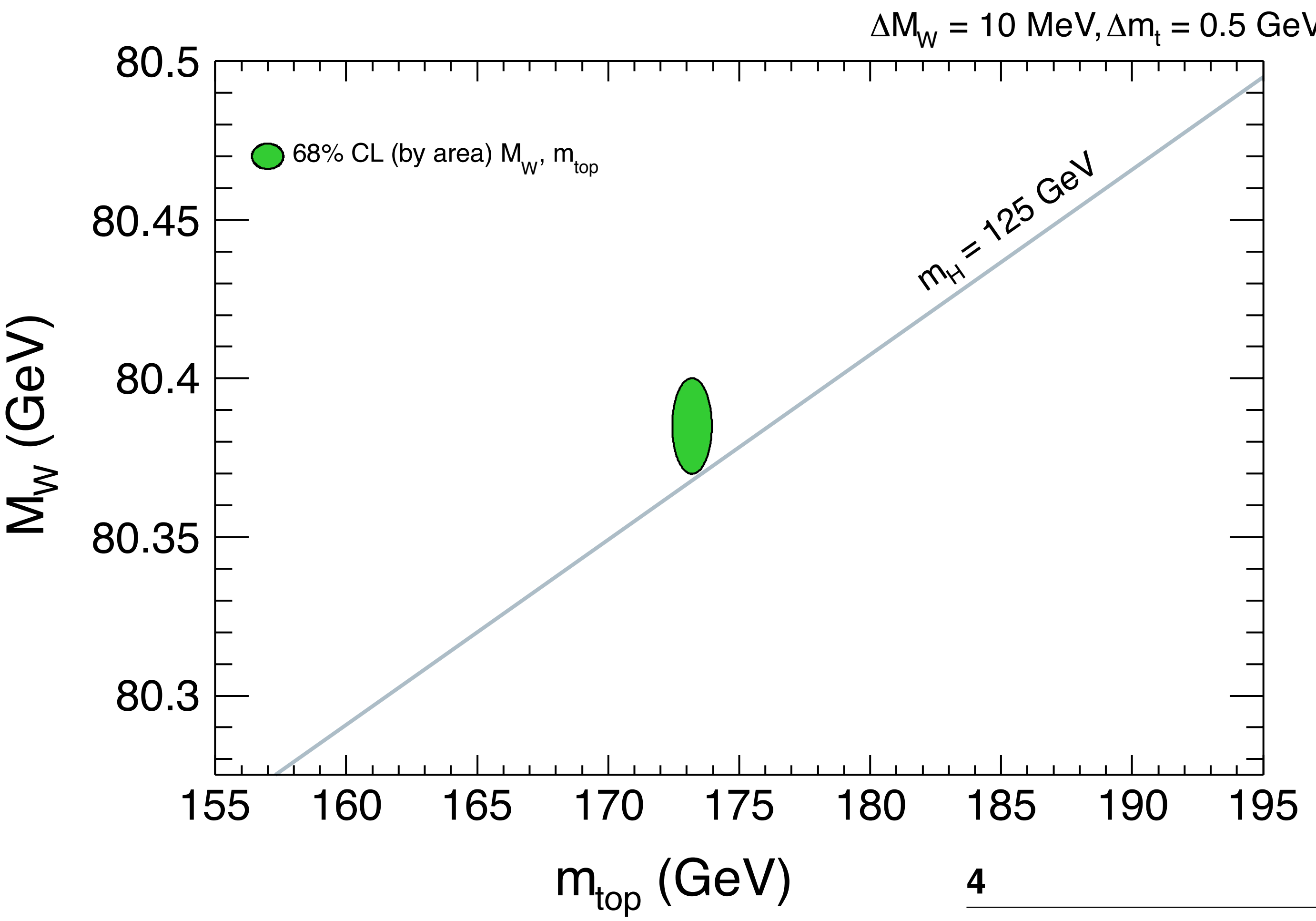
# Summary

- SM holds up well against precision tests
  - Tevatron measurements still yet to come
  - W mass measurements with full dataset to better than 10 MeV precision (theoretical prediction including $m_H$ to 11 MeV now)
  - Many precision measurements to come from LHC experiments
  - W/Z production physics will be verified again at Run 2 energy

- Many results which could not be shown
  - **ATLAS**: **https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults**
  - **CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP**
  - **CDF: http://www-cdf.fnal.gov/physics/ewk/**
  - **DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm**
- **Parallel talks by H. Yin (CDF+DØ), D. Tsionou (ATLAS), H. Yoo (CMS)**

# Backup

# W Mass: future?




Future Tevatron $m_W$ and Tevatron+LHC $m_t$

or... back to $e^+e^-$ ?

4 2 The LEP3 Physics case

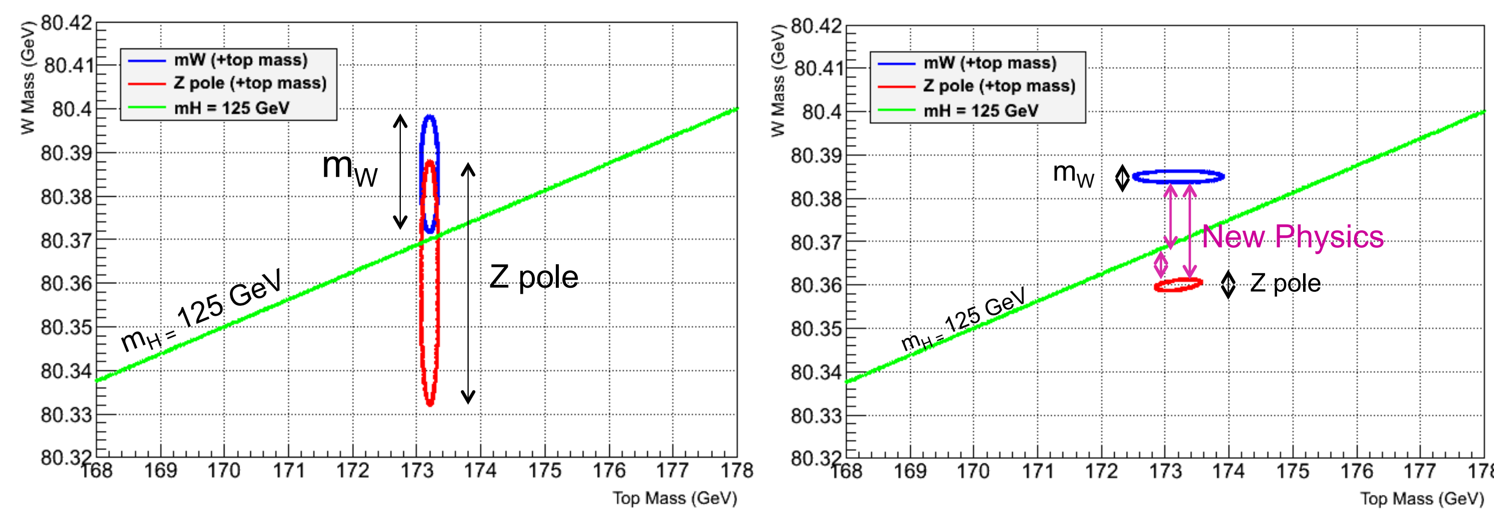
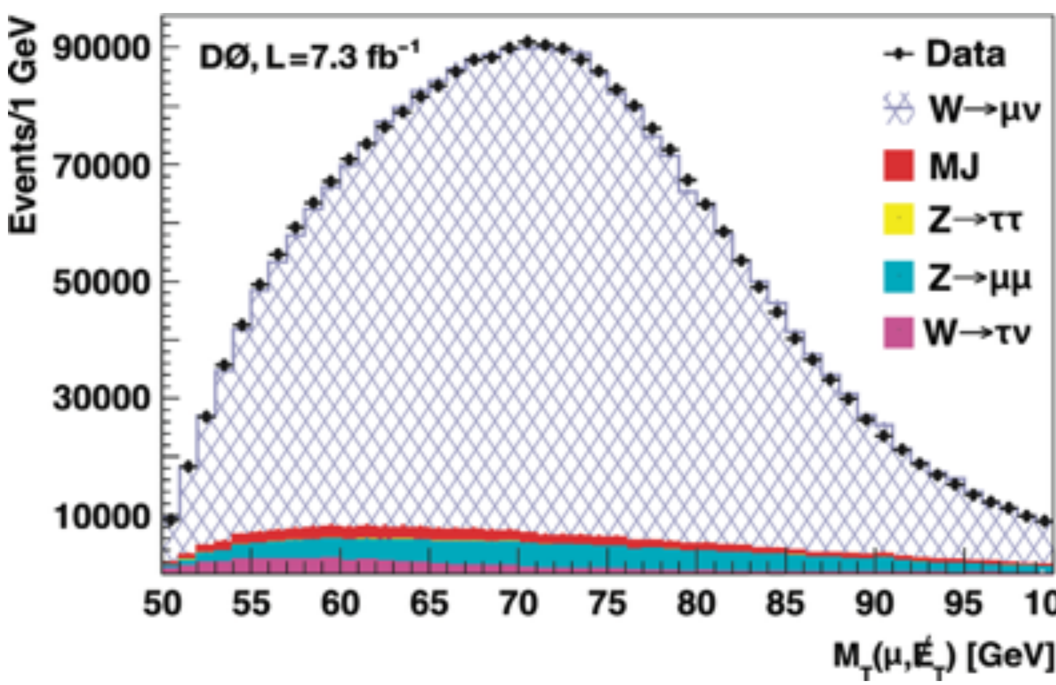
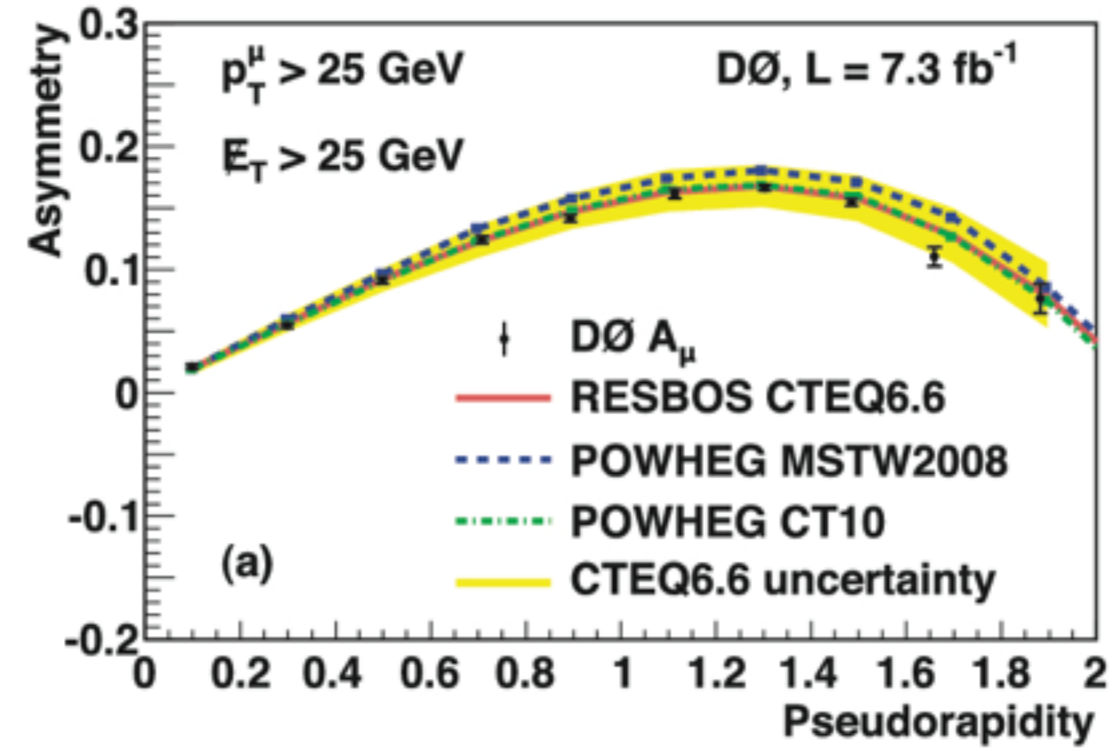


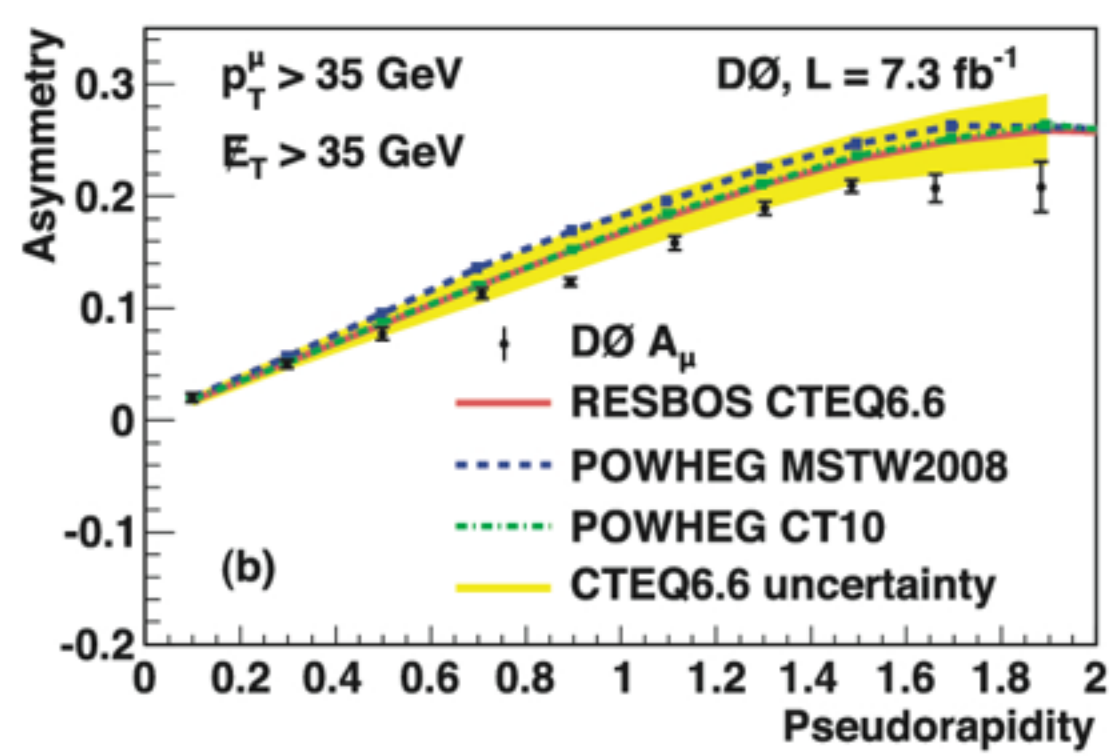

Figure 3: The effect of improving the precision of the top mass measurement by a factor 10 (left), or the precision of the Z pole and the W mass measurements by factors of 25 and 10, respectively (right), in the $(m_W, m_{top})$ plane.

From **CMS Note 2012/003**
P. Azzi *et al.*
"Prospective Studies for LEP3 with the CMS Detector"

# DØ muon charge asymmetry




- Data reweighted to remove discrepancy between solenoid polarities